BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING
FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AUTOMOTIVE ENGINEERING
ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

LOCAL CONTROL OF SEAT VENTILATION AND ITS IMPACT ON HUMAN THERMAL COMFORT
REGULACE VENTILOVANÉHO SEDADLA AUTOMOBILU S OHLEDEM NA TEPELNÝ KOMFORT ČLOVĚKA

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

AUTHOR Ing. Jaroslav Matuška
AUTOR PRÁCE

SUPERVISOR Bc.Ing. Jan Fišer, Ph.D.
VEDOUCÍ PRÁCE

BRNO 2018

Master's Thesis Assignment

Institut: Institute of Automotive Engineering
Student: **Ing. Jaroslav Matuška**
Degree programm: Mechanical Engineering
Branch: Automotive and Material Handling Engineering
Supervisor: **Bc.Ing. Jan Fišer, Ph.D.**
Academic year: 2017/18

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Local Control of Seat Ventilation and Its Impact on Human Thermal Comfort

Brief description:

The aim of thesis is to perform the measurement of a ventilated seat with a special focus on human thermal comfort. Furthermore, to compare different combinations of ventilation intensity and air distribution on a seat cushion and a backrest. Afterwards, based on the analysis of the measurement results, to propose optimal seat ventilation control.

Master's Thesis goals:

Ventilated seats bring new possibilities how to improve the passenger's thermal comfort with relatively low power consumption. This technology do not only improve thermal comfort but also enables the driver to fully concentrate on driving, which can also increase overall driving safety. In order to optimize thermal comfort using this technology, it is necessary to achieve an optimal way of distributing air (push / pull) and the amount of intake / exhaust air.

Recommended bibliography:

Vehicle thermal management: heat exchangers & climate control. Editor Gursaran D. MATHUR. Warrendale: Society of Automotive Engineers, c2004. PT (SAE). ISBN 0-7680-1445-X.

NILSSON, H. O. a HOLMER, I. Comfort climate evaluation with thermal manikin methods and computer simulation models. Indoor Air [online]. 2003, 13(1), 28-37 [cit. 2017-10-24]. DOI: 10.1034/j.1600-0668.2003.01113.x. ISSN 0905-6947. Dostupné z: http://doi.wiley.com/10.1034/j.1600-0668.2003.01113.x

ČSN EN ISO 14505-2. Ergonomie tepelného prostředí – Hodnocení tepelného komfortu ve vozidlech. Český normalizační institut (2007).

DALY, S. Automotive air-conditioning and climate control systems. 1st ed. Boston: Elsevier Butterworh-Heinemann, 2006. ISBN 9780750669559.

Students are required to submit the thesis within the deadlines stated in the schedule of the academic year 2017/18.

In Brno, 20. 10. 2017

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ FAKULTA STROJNÍHO INŽENÝRSTVÍ DĚKANÁT 11

L. S.

prof. Ing. Václav Píštěk, DrSc.
Director of the Institute

doc. Ing. Jaroslav Katolický, Ph.D.
FME dean

ABSTRACT

The master's thesis is focused on the measurement of the ventilated seat with special consideration on the human thermal comfort. It describes and summarises the heat transfer of the human body with surroundings and the human thermoregulation. It also captures and evaluates selected approaches to thermal comfort assessment. It deals with the comprehensive overview of the thermal-comfort units in the automobile. It introduces used measurement methodology for the thermal comfort of the ventilated seat, and then analyses and evaluates the particular acquired data.

KEYWORDS

Heat transfer, thermoregulation, thermal comfort, thermal-comfort units in an automobile, ventilated seat, climate chamber measurement and thermal comfort assessment.

ABSTRAKT

Diplomová práce je zaměřena na měření ventilovaného sedadla s ohledem na tepelný komfort člověka. Popisuje a shrnuje tepelný přenos lidského těla s okolím a termoregulaci člověka. Dále zachycuje a zhodnocuje vybrané přístupy hodnocení tepelného komfortu. Zabývá se komplexním přehledem tepelně komfortních jednotek v automobilu. Představuje použitou metodu měření tepelného komfortu u ventilovaného sedadla, načež analyzuje a vyhodnocuje jednotlivá získaná data.

KLÍČOVÁ SLOVA

Přenos tepla, termoregulace, tepelný komfort, tepelně komfortní jednotky v automobilu, ventilované sedadlo, měření v klimatické komoře a hodnocení tepelného komfortu.

BIBLIOGRAPHIC CITATION

MATUŠKA, J. *Local Control of Seat Ventilation and Its Impact on Human Thermal Comfort*. Brno, 2018. Master's thesis. Brno University of Technology, Faculty of Mechanical Engineering, Institute of Automotive Engineering. 108 pages. Master's thesis supervisor Bc. Ing. Jan Fišer, Ph.D.

BIBLIOGRAFICKÁ CITACE

MATUŠKA, J. *Regulace ventilovaného sedadla automobilu s ohledem na tepelný komfort člověka*. Brno, 2018. Diplomová práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav automobilního a dopravního inženýrství. 108 s. Vedoucí diplomové práce Bc. Ing. Jan Fišer, Ph.D.

DECLARATION

I declare that I have written this master's thesis on my own according to the instructions of my master's thesis supervisor Bc. Ing. Jan Fišer, Ph.D., and using the sources listed in references.

Brno, 25th May 2018 ……..……..……………………………………………..

Ing. Jaroslav Matuška

ACKNOWLEDGEMENT

First of all, I would like to thank Dr Jan Fišer for the advice, feedback and motivation he gave me not only during the writing of my diploma thesis. Furthermore, Dr Viktor Bader, who allowed me to write the thesis in his department within Volkswagen Group research, and Albrecht Noetzel for his technical advice. Last but not least, my mother for her heartfelt upbringing and my father, brother, and primarily Klára Samohýlová for trust and support throughout my master study.

PODĚKOVÁNÍ

V první řadě bych rád poděkoval panu doktoru Janu Fišerovi za rady, zpětnou vazbu a motivaci, kterou mi dával nejen po dobu psaní mé diplomové práce. Dále doktoru Viktoru Baderovi, který mi umožnil psát práci na jeho oddělení v rámci koncernového výzkumu Volkswagenu a Albrechtu Noetzelovi, za jeho technické rady. V neposlední řadě poté mojí matce za její srdečnou výchovu a mému otci, bratrovi a především Kláře Samohýlové za důvěru a podporu během celého mého magisterského studia.

CONTENT

INTRODUCTION

Increasing mobility has led that people spend more time inside the vehicles. Therefore, the thermal comfort of a driver and passengers has become, among other things, a crucial issue in the development of a new car. On the other hand, the other major problem is simultaneous to reduce the energy consumption at the lowest possible level.

For example, in the United States is annually consumed approximately 26 billion litres of fuel for cooling interiors of vehicles.

Moreover, 85% of trips involve an average distance fewer than 18 kilometres and with time durations from 15 to 30 minutes. Hence, through this period the passengers mostly do not achieve the thermal comfort range.

This can be overcome mainly by optimisation of thermal management in a cabin, especially focusing on the local thermal comfort. This leads to an overall reduction of fuel consumption and exhaust emissions. Where the most effect of the optimisation is in the case of electric or hybrid vehicles because desired thermal comfort conditions are at the expense of the range.

One of the parts enabling the local thermal comfort is ventilated seat. It can relatively quickly provide sufficient cooling of the human body, especially parts of the human body which are in contact with the seat. Despite the various design solutions of the ventilated seat, there are two main approaches concerning the air distribution which is the blowing and the suction mode. Therefore, it was done the measurement of the specially modified seat which enabled both blowing and suction to detect the differences regarding the local thermal comfort of the seat. [1, 2]

MOTIVATION

My motivation for the topic concerning to ventilated seats was to combine and utilise my acquired knowledge from the academic area and internship experiences in the car seat development companies such as Johnson Controls (now Adient) in Slovakia and recent cooperation with Sitech Sitztechnik in Germany. As well as my overall interest in the automotive industry.

During my studies, I wanted to take the most opportunities which came my way. This approach allowed me to gain my knowledge not only in depth but also in width. In addition to my internship in the car seat company, I have also completed three student internships at various international manufacturing and development factories with the latest in Volkswagen Group research in Wolfsburg in Germany. Moreover, it was supported by one-semester study abroad, where I also attended selected subjects from the Faculty of Management.

Therefore, the diploma thesis allowed me to use all my experiences and apply it directly to the practical outlet. At last, this thesis brought me the added value of being written in English.

TARGETS AND LIMITS OF THE WORK

The target of this thesis is to accomplish the measurement of the specially modified ventilated seat with a special focus on human thermal comfort.

Furthermore, to compare different air distribution meant blowing and suction, and observe the ventilation intensity on the cushion and the backrest.

Afterwards, based on the analysis of the measurement results, to assess optimal seat ventilation control.

Firstly, it will be described and summarised the basic principles of heat transfer on a surface and inside a human body together with human thermoregulation. Secondly, it will be captured and evaluated selected approaches to thermal comfort assessment. Thirdly, it will be dealt with the comprehensive overview of the thermal-comfort units in the automobile. Therefore, this part will cover the general appraisal of the automobile thermal comfort issue to understand the overall evaluation of ventilated seat better.

In next, practical, part it will be introduced the used measurement methodology of the ventilated seat for the thermal comfort inquiring. Finally, it will be analysed and evaluated the particular acquired data with possible suggestions for further development.

The measurement methodology is based on the long-term experience of the climate chamber and thermal comfort laboratories as well as it is adapted to their possibilities. This concerns mainly the used equipment and number of tested persons.

1 Human Body Thermal Interaction

At the very beginning, the basic principles of heat transfer on a surface and inside a human body will be described. In general, heat transfer concerning the human body can be divided into two systems: passive and active. Firstly, the passive system will be clarified in two separated parts: focusing on heat transfer with surroundings and concerning the production and transmission of heat within the human body. Secondly, it will be covered the active system represented by thermoregulation.

1.1 Passive System – Heat Transfer with Surroundings

A thermal balance has a fundamental influence on the thermal state of a person. It expresses the relationship between the amount of heat produced and the amount of heat discharged from a human body to the surroundings. If there is a thermal equilibrium, the human body produces heat that is transmitted to the surroundings through radiation, conduction, convection, evaporation, and breathing. On the other hand, basic heat transfer from surroundings, which human is exposed in a car cabin is depicted in Figure 1. [3]

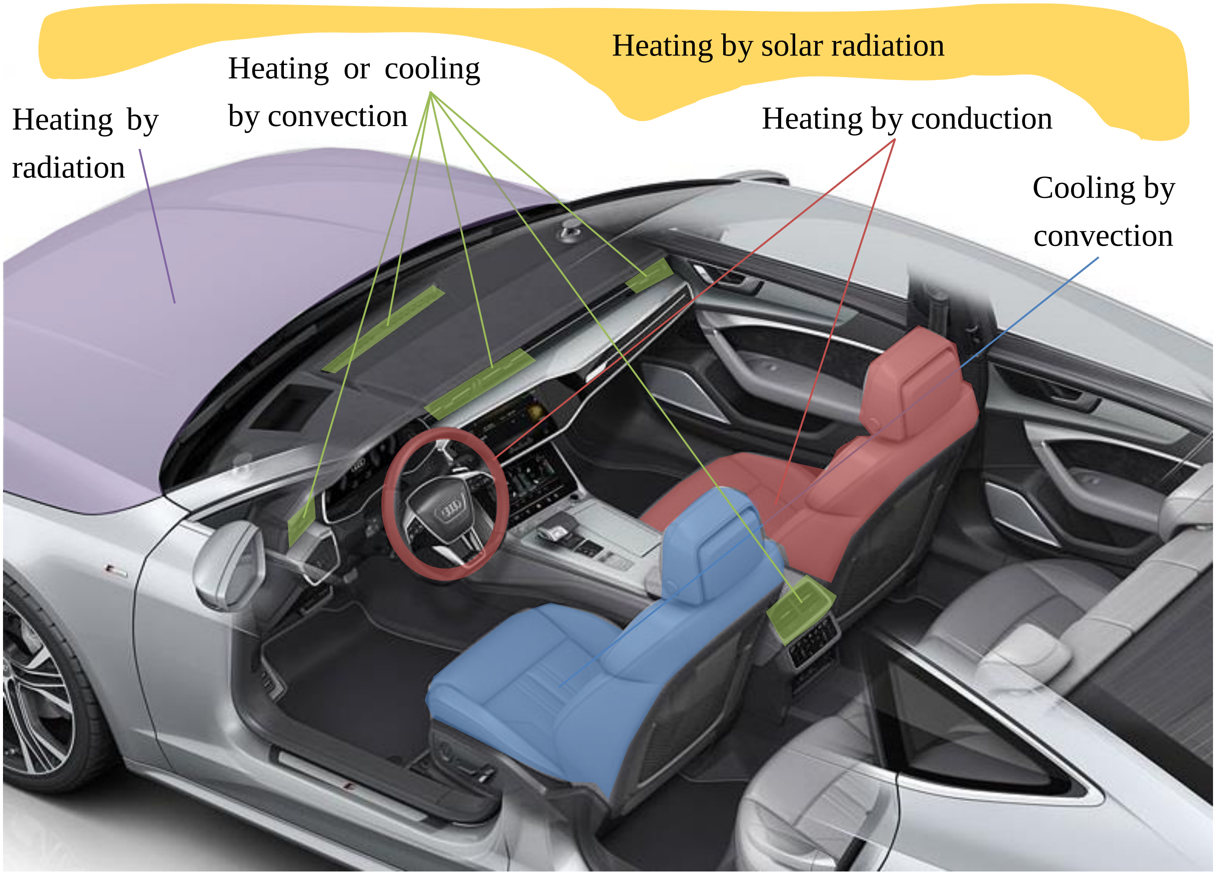


Figure 1) Heat transfer from surroundings in a car cabin [4]

1.1.1 THERMAL RADIATION

Radiation represents the heat transfer between bodies through electromagnetic waves. Each body with a temperature higher than 0 K emits a portion of its energy in the form of electromagnetic waves. By the impact of these waves, energy is absorbed and transformed into internal energy, which results in an increased temperature.

Radiation is in our climatic conditions a significant body-heat loss factor accounting for up to 61% of total heat losses. Radiation heat transfer is the only heat transfer process that does not require the presence of a material transfer medium. Therefore, it can also take place in a vacuum where it has the maximum effect.

The properties of radiation-related substances are transmissivity, absorptivity, reflexivity, and emissivity. Thus, the composition of matter permits, absorbs, reflects and radiates radiation. According to 1st Kirchhoff's law of optics, the sum of reflexivity, absorptivity, and transmissivity is equal to 1. For most solid non-transparent bodies, the transmissivity is zero. In the case of long-wave radiation, according to the 2nd Kirchhoff optics law, in the state of thermal equilibrium, the absorbance is equal to emissivity.

The amount of total radiated heat per unit of time is expressed by the Stefan-Boltzmann law. According to that, the amount of radiated energy is directly proportional to the fourth power of the absolute body temperature. However, the surrounding bodies act on the human body with the same mechanism. In the car cabin, it is mainly heat emitted from an engine bay and a solar radiation. The total radiated energy is therefore given by the difference between the four powers of the surface temperature of the human body and the temperature of the bodies in its immediate surroundings. The generalization of the Stefan-Boltzmann law is Planck's radiation law, which found application in quantum physics.

The intensity of the electromagnetic radiation is further dependent on the frequency, respectively on the wavelength of radiation. The electromagnetic spectrum is shown in Figure 2.

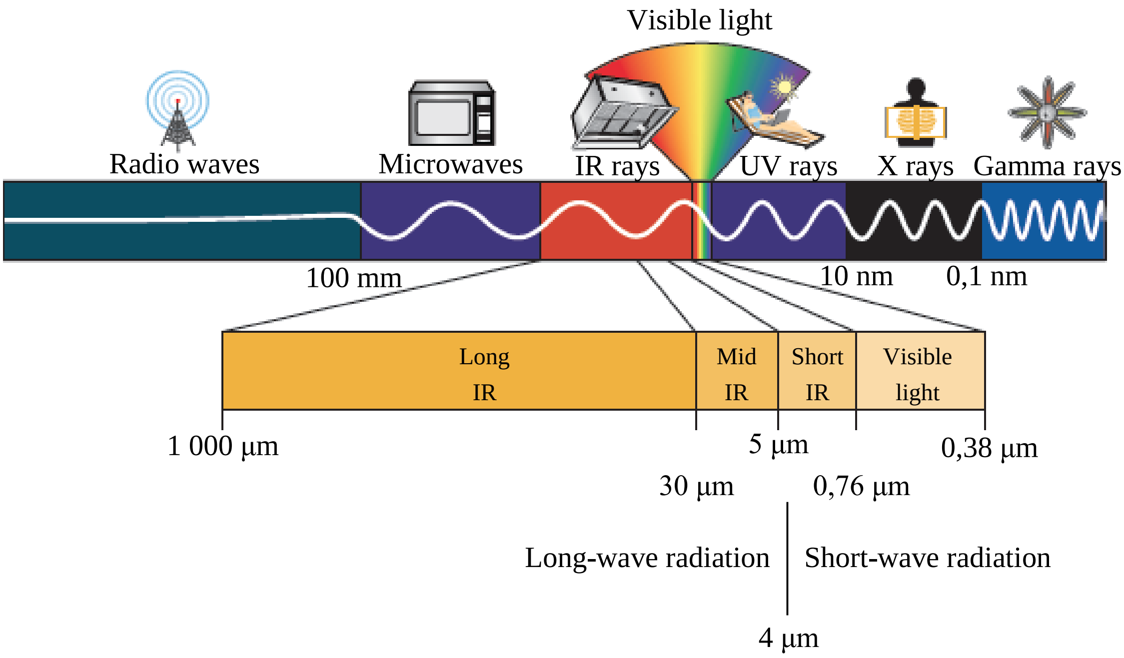


Figure 2) Electromagnetic spectrum [5]

From the point of view of the human body, thermal perception is necessary to distinguish mainly between long-wave and short-wave radiation. Long-wave radiation, with a wavelength more than 4 µm, is also called thermal Infrared (IR) radiation. It is typically radiated by the bodies with a surface temperature up to 725 °C. Short-wave radiation, with a wavelength of fewer than 4 µm, is typically represented by solar radiation and it consists of near-infrared (NIR), visible and near-ultraviolet (NUV) radiation.

Human skin has particularly high shortwave absorbency and long-wave emissivity of about 0,97 to 1.With the decreasing wavelength of radiation, the same irradiation dose causes more serious tissue damage. UV-A radiation (wavelength 400-315 nm) is considered to be harmless. It accounts for up to 99% of the entire UV spectrum released by the earth's atmosphere. UV-B (wavelength 315 - 280 nm) has a long-term unhealthy effect on tissues. It could cause skin burns and skin cancer. UV-C (wavelength 280 - 100 nm) is the most dangerous radiation. It penetrates deep into human tissues and uncontrolled doses can cause death. Nevertheless, most of the UV-B and UV-C radiation coming from the Sun is mainly absorbed by the Earth's ozone layer. [3, 6, 7]

1.1.2 THERMAL CONDUCTION

Thermal conduction is a process which takes place at the molecular (atomic) level. Heat is transmitted by vibrating the microscopic parts around their state of equilibrium and by interacting with each other. The surrounding particles collide and transfer part of their kinetic energy among themselves. The direction of the energy flow is given by a temperature gradient that goes from a warmer place to the place of lower temperature.

Heat transfer is described by Fourier's law. It determines the dependence of the specific heat flux on the temperature gradient and the coefficient of thermal conductivity, which expresses the ability of the substance to conduct heat.

In humans, heat exchange takes place by conducting the skin's contact with surrounding objects. In the car cabin, it is mainly a seat and a steering wheel, moreover a gear lever and a floor. Air is considered to be a heat insulator, so the conduction can be neglected according to contact with the skin. Conduction also plays a significant role in the penetration of heat through clothing, which is in close contact with the surface of the human body. On the contrary, inside the human body, the blood is well conductive and thermal insulation mainly consists of fat tissue. [3, 8]

1.1.3 THERMAL CONVECTION

Convection is the heat transfer due to bulk movement of molecules within fluids such as gases and liquids. Convection is realized by streaming fluid which flows around the surface of the body and is described by Newton's law of cooling. Which defines the total heat flux dependence on the value of the heat transfer coefficient and the difference between the body surface temperature and the ambient fluid temperature. The heat transfer coefficient includes several important parameters such as flow characteristic (laminar, turbulent), the physical properties of the fluid (viscosity, wettability), the geometry of the flow etc. The coefficient value is obtained on the basis of similarity criteria such as Reynolds, Prandtl, Nusselt and Grashof number, empirically by the case or by CFD simulation.

Convection, together with radiation, is most involved in the heat exchange between a human and surroundings. In the car cabin, convection is mainly represented by HVAC system and an open window.

Overall, two types of convection can be distinguished. First, free or natural convection, which occurs when fluid motion is caused by buoyancy forces that result from the density variations due to variations of the fluid thermal temperature. The mass of the warmer fluid is less dense. For this reason, the warmed mass is displaced up, while the colder and denser mass of fluid goes down. Second, forced convection, which occurs when a fluid is forced to flow by an external source such as fans, pumps etc. which creates an artificially induced convection current. [3, 9]

EVAPORATION

Evaporation is the special case of convection with a phase transformation. The human body excretes sweat on a skin. If the ambient air is not saturated, evaporation occurs which cools down the skin. In order to allow the substance to be transformed, latent heat of vaporization has to be delivered. The overall evaporation losses are dependent on the difference between the partial pressures of saturated water vapour on the skin and the vapours in the ambient air. The simplified principle of evaporation is shown in Figure 3.

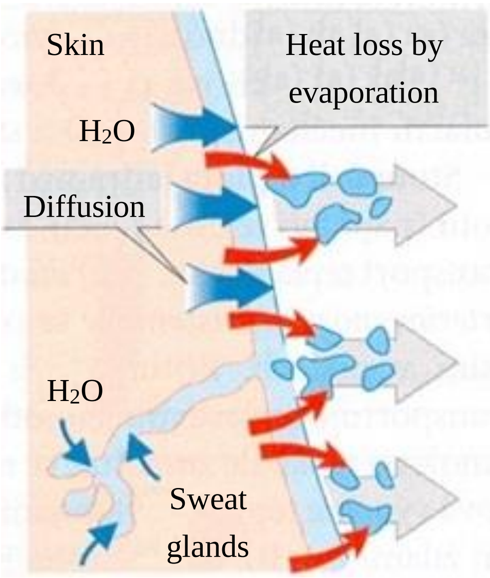


Figure 3) Simplified principle of evaporation [10]

Generally, evaporation is based on the principle of diffusion, which is described by Fick's first law. It states that the diffusion flux is determined by the amount of substance that passes through the surface and it is directly proportional to the negative concentration gradient. Where the proportionality constant is a diffusion coefficient that characterizes the ability of a substance to diffuse in a particular environment.

Under normal conditions, heat transfer by evaporation i.e. sweating is about 13 % of the total heat transfer from the human body. It is the most effective way of heat losses that prevents overheating of the body in conditions where the ambient temperature is higher than body temperature. If the human faces extreme temperatures, the human body can lose up to 1 litre of perspiration per hour. [8, 10, 11]

RESPIRATION

Respiration is a combination of forced convection and phase evaporation. An air flows through the respiratory tract during exhalation and inhalation, which enables heat transfer to the surroundings by convection. At the same time, the water evaporates from the mucous membranes, thereby the exhaled air is humidified, which results in heat transfer by evaporation at the same time. The intensity of breathing has a great influence on heat transfer by respiration because it has an influence on the total amount of air exchanged with the surroundings. Relationships for the determination of heat losses by respiration are purely empirical. They are usually expressed depending on the activity performed, which is related to the amount of inhaling and exhaling air. [3]

1.2 PASSIVE SYSTEM – HEAT TRANSFER WITHIN A HUMAN BODY

Human produces metabolic heat which is produced as a by-product of metabolic changes and muscle activity. Most heat is made in organs with the highest biochemical activity, such as heart, liver, kidneys and brain.

Nevertheless, during a physical exercise, the human body burns energy and produces mechanical work, where the most of the energy is transformed into the heat which is produced by the muscle tissue. In total, muscles produce up to 90 % of the total heat in this situation. The overall percentage of organs body weight and percentage of organs heat producers are shown in Figure 4. Nonetheless, this metabolic transformation of energy requires a sufficient amount of oxygen which is delivered from lungs by the blood circulation. It happens that the body increases the amount of inhaled air, a breathing frequency and heart rate which increases a blood flow by vessels.

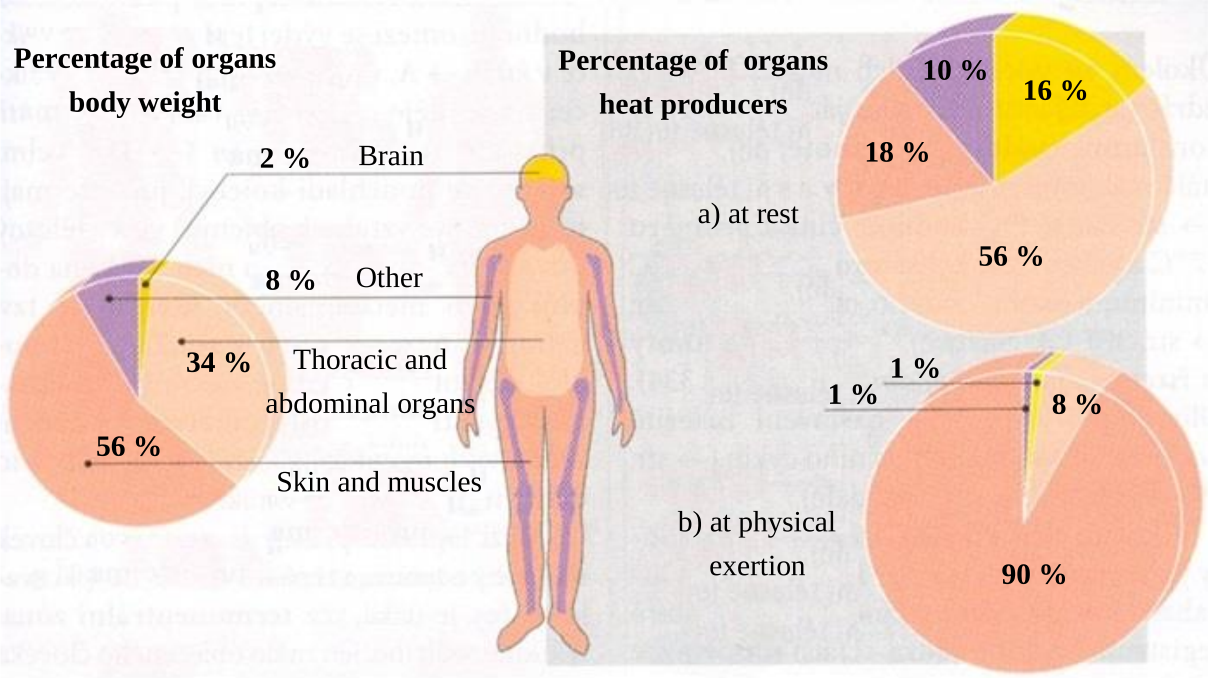


Figure 4) Percentage of organs body weight and organs heat producers [10]

The total amount of energy released depends on the weight of a person, the surrounding conditions and his activity. For instance, in the cold environment, the rate of metabolic changes increases, and muscular activity is complemented by muscle tremors. Nonetheless, under normal conditions in a calm position human produces heat around 100 W.

If the ambient temperature is lower than the body temperature, the heat penetrates the surface by conduction through the layers of the tissue (such as muscle, fat, subcutaneous tissue and skin) and goes into the surroundings. As has already been said, the fat layer limits this heat transfer due to its insulating properties and has a great effect on the overall reduction of heat losses of the human body. In general, people with more fat tissue are more resistant to cold.

In addition to conduction, heat transfer from the surface of organs is accomplished by the convection of blood through large vessels. These are further branched into capillary and venous plexuses, which allow blood to flow through the tissues near the surface of the body. Afterwards, heat is taken from the skin to the surroundings.

Subsequently, the blood returns to the heart via veins. They create two systems on the limbs. First, a surface system that is visible through the skin and second, a deep system that is located along the paths of the arteries between the muscles. Blood inside the deep veins, which is relatively colder, returns from the limbs towards the heart. At the same time, the blood is heated by the bloodstream of warmer arteries which flow opposite direction and which are immediately next to veins. It is called counter current heat exchange. [3, 10, 12]

1.3 ACTIVE SYSTEM – THERMOREGULATION

Under ideal circumstances, the amount of heat produced and the amount of heat discharged is in equilibrium. For instance, the ideal ambient temperature for a naked human is 28 °C. However, the human is normally exposed to a wide range of climatic conditions in which passive systems can be ineffective to sustain a thermal balance. To achieve this balance, therefore, is the thermoregulation, i.e. the active processes that cause the body to cool down or warm up. Percentage distribution of total heat losses according to different ambient temperatures is shown in Figure 5. Overall, the range of an internal body temperature is maintained from 35,8 °C to 37,4 °C.

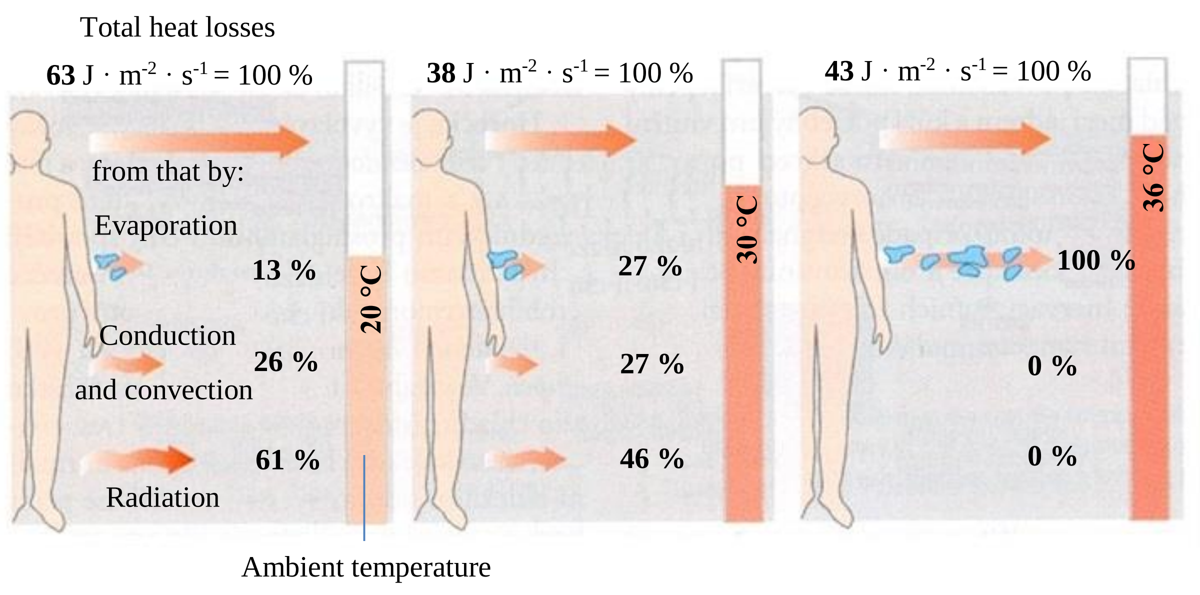


Figure 5) Percentage distribution of total heat losses according to different ambient temperatures [10]

The body temperature is centrally controlled by the brain, more precisely its specific part the hypothalamus. It evaluates the signals received from the peripheral thermo-receptors in the skin and the internal thermo-receptors in the spinal cord, the abdominal cavity, around the large veins, and in the hypothalamus itself. Peripheral thermo-receptors are further divided into cold and thermal bodies. They are represented by loose nerve endings that are not evenly distributed throughout the human body. That means some parts are more sensitive to cold or heat than others.

For example, a female sensitivity to 20 °C cold and 40 °C hot stimuli at rest and ambient temperature of 22 °C is shown in Figure 6 and Figure 7. The higher the number, the higher the thermal sensitivity. Generally, it can be said, that a significantly higher magnitude sensation is seen for the cold stimuli. The anterior torso is more sensitive than the posterior torso. And the lateral lower back is less sensitive than most locations across the torso and head region.

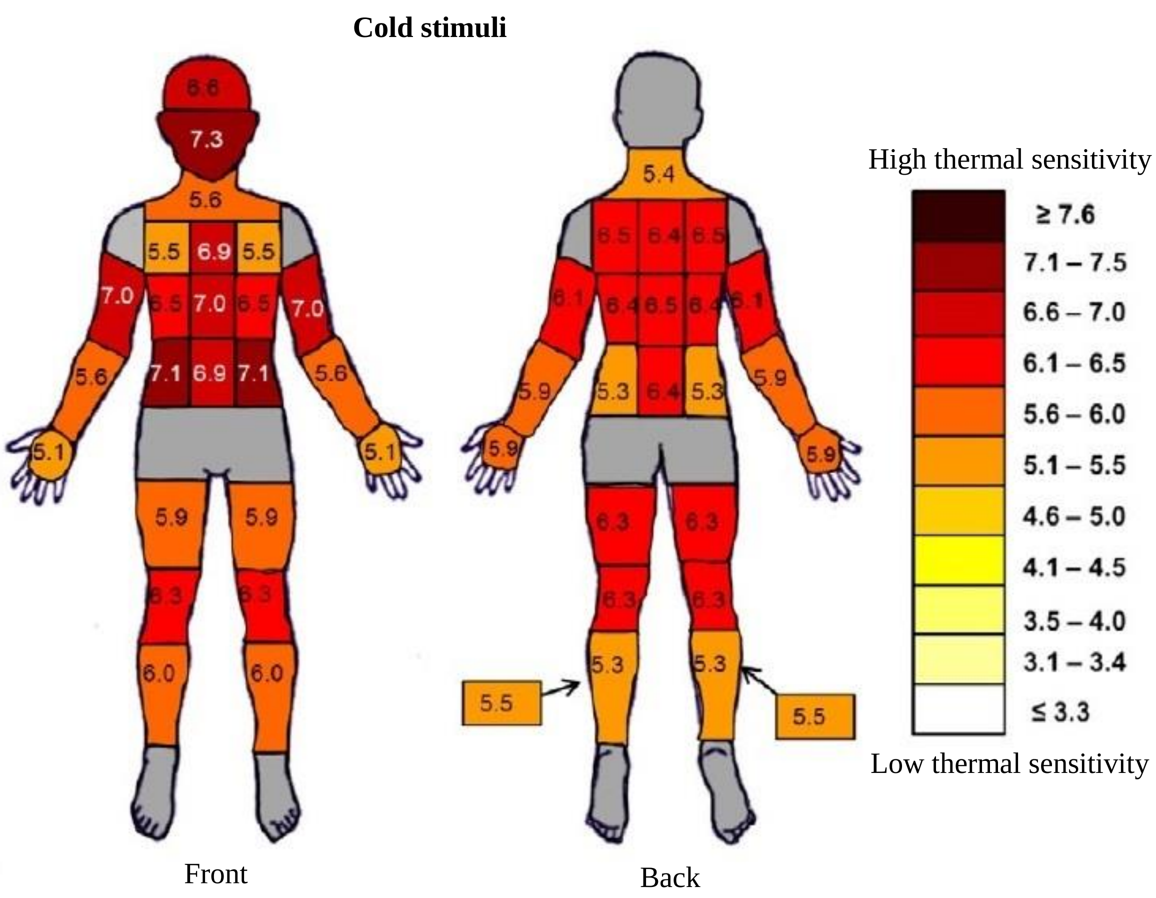
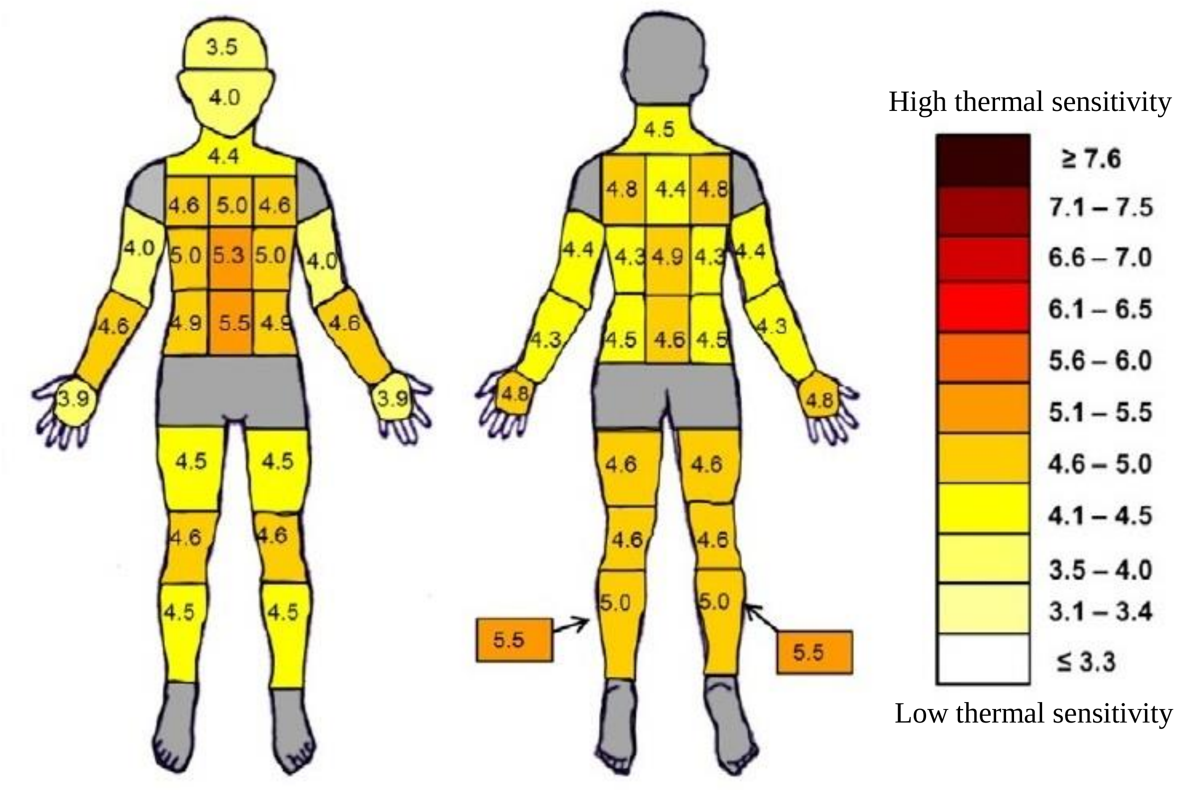


Figure 6) Female body map of mean thermal sensations for cold stimuli [14]

Hot stimuli



Front Back

Figure 7) Female body map of mean thermal sensations for hot stimuli [14]

Finally, the thermo-receptors response employed by the body to maintain thermal balance is initiated and controlled in response to a load error. That is a body temperature which is transiently above or below the set point. A core temperature above the set point creates a positive load error, leading to heat loss (vasodilatation, perspiration) being turned on. A core temperature below the set point creates a negative load error, resulting in heat gain (vasoconstriction, muscle tremors, thermogenesis) being initiated. In each case, the resultant heat transfer decreases the load error and helps return the body temperature to a steady state. [3, 10, 15, 14]

1.3.1 BODY TEMPERATURE DECREASING

VASODILATION OF BLOOD VESSELS

Vasodilation of blood vessels is a reaction to warm environment. It spreads the cross-section of the blood vessels and allows a higher blood flow to the peripheral parts of the body in order to increase the heat transfer. The principle of vasodilation is shown in Figure 8. A concomitant phenomenon is the blood circulation of a skin, where the skin redness can be observed, which increases the surface temperature of the skin and heat is passively transferred to the surroundings. Vasodilation of blood vessels could increase up to eight times heat transfer from the body to the surface. However, if the ambient temperature is equal or higher than the surface temperature of the body, this method becomes ineffective. [16]

PERSPIRATION

Perspiration is the most effective way of heat losses, as it has been already said. Especially, if the ambient temperature is above 36 °C, the other heat losses such as radiation, convection and conduction are completely ineffective. During perspiration, the human body actively excretes sweat on a skin to be passively evaporated to the surroundings. The sweat itself consists mainly of water containing Na +, K + and Cl- ions, lactic acid and urea. [3, 10]

1.3.2 BODY TEMPERATURE INCREASING

VASOCONSTRICTION OF BLOOD VESSELS

Vasoconstriction of blood vessels is a reaction to the cold environment. It narrows the cross-section of blood vessels, especially in the limb areas. Therefore, less blood gets into the circumjacent tissue, thereby it reduces the body's thermal losses to the surroundings. The principle of vasoconstriction is shown in Figure 8. Thus, the body prevents vital organs from hypothermia. However, it happens at the expense of marginal parts of the body, such as limbs and especially fingertips, which causes frostbite in extremely cold conditions. [3]

MUSCLE TREMORS

Muscle tremors are the random involuntary contraction of superficial muscle fibres, which does not limit heat loss but rather increases heat production. A human body can increase his metabolic heat production about three to four times during intense shivering. Many individual factors contribute to muscle tremors. Nonetheless, one important factor is again body fatness. For instance, a human with very little subcutaneous fat of 2 to 3 mm thickness starts shivering after 40 min at 15 °C and 20 min at 10 °C, while a man who has more insulating fat of 11 mm may not shiver at all at 15 °C and after 60 min at 10 °C. [15]

THERMOGENESIS

Chemical thermogenesis occurs when a body is exposed to the cold environment for a longer period of time, for example over a week. It is the metabolic thermoregulation which is evinced by an intensification metabolic changes within the body and hence the increase of heat production. [3]

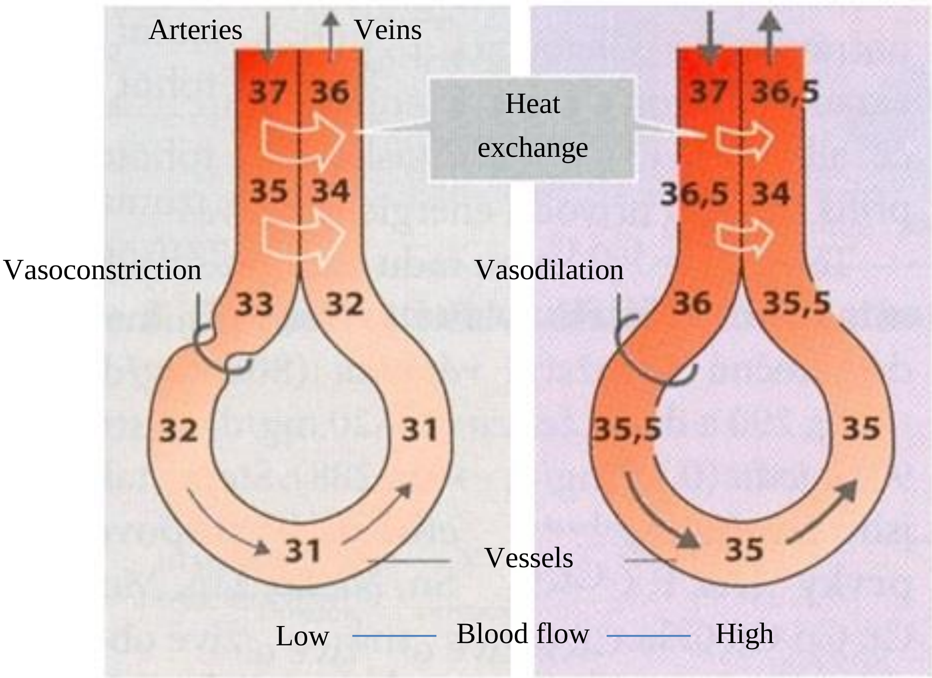


Figure 8) Vasoconstriction and vasodilation of blood vessels principle [10]

1.4 Evaluation

In general, the human body thermal interaction can be divided into the passive and the active system. The passive system characterizes the physical properties of the human body and describes heat transfer with surroundings such as radiation, conduction and convection, including evaporation and respiration. As well as it describes heat transfer and production within the human body.

On the other hand, the active system represents the human nervous system. Based on stimuli from thermo-receptors, it controls thermoregulatory responses and thus regulates thermal mechanisms for decreasing or increasing the body temperature.

It can be pointed, that the human body under normal conditions produces heat around 100 W. At rest, the most heat is produced by thoracic and abdominal organs, around 56 %. However, at physical exertion, the skin and muscles can produce up to 90 % of total heat.

If the ambient temperature is 20 °C, the most of heat losses are transferred to surroundings by radiation up to 61 %, while evaporation is only 13 %. Nonetheless, when the ambient temperature reaches around 36 °C, means the higher temperature than a body temperature, the most effective way of heat losses is just evaporation, while the other heat losses are completely ineffective.

Besides, the human body reacts differently to cold and hot stimuli. As well as the anterior torso is more sensitive than the posterior torso and the lateral lower back is less sensitive than most locations across the torso and head region.

Finally, it can be said, that the passive system represents the human body and the active system represents thermoregulation, where both systems are interconnected.

2 THERMAL COMFORT

After the explanation of the basic principles of heat transfer, the thermal perception of human on the environment will be introduced. Since the final effects on the surface heat transfer of the human body are important factors for heat balance and for the perception of the thermal conditions. Firstly, the general expression of thermal comfort will be discussed. Then, it will be continued by acquaintance with human physiology models and the historical overview of thermal comfort models. Finally, it will be highlighted four thermal comfort scales, which enable to evaluate the subjective thermal perception of tested persons.

Thermal comfort is defined by the American standard ASHRAE 55 (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) as a subjective concept related to physical and psychological human well-being in agreement with the surroundings. Thermal comfort is assured by all the factors that influence heat transfer between the human body and surroundings as well as psychological state of the specific person. This way it can differentiate between factors connected with the human psychological and physiological condition, the clothing, and the ambient environment. Nevertheless, the overall human thermal comfort essentially depends on an interaction between following six parameters, which affect thermal sensation the most:

- air temperature,
- mean radiant temperature (ambient surface temperature),
- air velocity,
- relative humidity,
- physical activity (metabolic rate),
- clothing thermal resistance.

Every person evaluates thermal comfort based on subjective perception. Therefore, thermal comfort is a purely subjective variable. It is based on series of measurements and queries of larger groups of respondents. Then it is statistically determined the average thermal sensation, which most of the people preferred. Thereafter, thermal comfort can describe how satisfied or dissatisfied the human is.

In general, for a steady state, the physiological conditions of thermal comfort at low activity levels are described as follows:

- internal body temperature 36,6 to 37,1 °C,
- mean skin temperature 33 to 34,5 °C for man and 32,5 to 35 °C for women,
- local skin temperature is variable over the body but generally between 32 and 35,5 °C,

- temperature regulation is completely accomplished by vasomotor control of blood flow to the skin (no sweating / shivering present).

Furthermore, the thermal comfort research falls into two categories, the rational heat balance approach and the adaptive approach. The heat balance approach is the conventional approach developed by Fanger which emphasises the environmental conditions, whilst the more recent adaptive approach also takes into consideration the ability of people to adapt and change their environments to make themselves comfortable.

Moreover, it is also possible to divide the physical comfort sensation to a local and whole body thermal comfort. The whole body value only consists of a mean value, while the local values take into consideration effects on different body parts.

Finally, it can be said, that the thermal comfort assessment can be evaluated using approaches listed below. In any case, the most accurate results are achieved by using all these methods simultaneously. [1, 17, 18, 19]

- Human subjects response
- Sensors
- Thermal manikins
- Infrared thermography
- CFD models

2.1 HUMAN PHYSIOLOGY MODELS

The main goal of physiological models is to predict the thermal state of the human body and its response to environmental parameters. Models of human physiology can be distinguished by:

a) The division of the human body

- One-segment - the human body is taken as a whole, suitable for a homogeneous environment.
- Multi-segment - the human body is divided into several segments, the models distinguish the asymmetric effect of the environment.

b) The time consideration

- Stationary - they are suitable for long-term assessment of environmental conditions.
- Dynamic - they are also applicable to the study of sudden changes in the environment, they count with the accumulation of heat in the skin.

Physiological models are applied in thermal comfort examination as well as in medicine, army, sports, textile and shoe industry. They are also used to estimate the physical condition of a person under extreme conditions. For instance, cold water survival after the shipwreck, heat condition of a soldier in the desert in full armour, or an athlete during demanding activities. The advantage of these models is their wide use and the ability to predict parameters that cannot be determined directly by measurements. On the other hand, these models do not always coincide with reality, especially if they are used outside the range of the environment parameters for which they were created and validated. Nowadays, the development of computer technology makes it possible to carry out extensive CFD (Computational Fluid Dynamics) simulation of the indoor environment. By including a physiological model in CFD simulation, it is possible to analyse the quality of the indoor climate and its impact on humans. Nevertheless, in some applications such as simulation of car cabin environments, aircraft, etc., it can also assist to find out what influence a person has on the surrounding indoor climate.

Anyway, because each person is different (height, weight, the proportion of fats and muscles in the body, sex, race, etc.), it is ideal for the physiological model to respect the individual parameters of each person. This area is so-called individualized models, which are primarily represented by the Fiala and the Gagge individualized models. Nonetheless, individualized models demand the amount of input data required, but unlike conventional averaged models, they have a higher perceived value for a particular person. [3]

2.2 THERMAL COMFORT MODELS

Thermal comfort is related to temperature, but it is not the only important indicator. Prior to World War II, this issue was dealt with by Yaglou and subsequently by Bedford, whose thermal comfort scale is used up to now. In the early 1970s, Ole Fanger specified the basic and additional factors influencing thermal comfort in the interior of buildings. He defined the Predicted Mean Vote (PMV) index of the heat sensation assessment of a larger group of people and Predicted Percentage of Dissatisfied (PPD) index expressing the percentage of dissatisfied with the inner environment. In 1984, his method of thermal comfort assessment was established as a norm ISO 7730 – Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Another approach was chosen by Gagge, who used his physiological model to predict the mean skin temperature and the amount of water on the skin to calculate the TSENS thermal sensitivity index and the DISC thermal discomfort index. In 2003, Fiala defined the Dynamic Thermal Sensitivity (DTS) as the equivalent to the PMV index, which is also applicable to time-varying conditions. The index represents the overall thermal sensation, which depends on the mean skin temperature, its time change, and body core temperature. A historical overview of thermal comfort models is shown in Table 1.

Table 1) Thermal comfort models overview [1]

Year	Author	Model description
1923	Yaglou	Introducing the effective temperature index
1936	Bedford	Scale of thermal sensations, empirical model
1970	Fanger	PMV-PPD model, from 1984 in ISO 7730
1971	Givoni	Empirical model of thermal comfort
1986	Gagge	Thermal comfort index TSENS, DISC
1989	Wyon	Model of equivalent temperature
1992	Hagino	Empirical model of thermal comfort in a car (for Nissan)
1992	Taniguchi	Influence of cold air on sensation of a face (for Toyota)
1992	Ingersoll	3-segment model Gagge, coupled with the PMV index
1993	Gan	Stationary PMV-PPD model, CFD utilization
1994	Wang	Dynamic model of thermal comfort
1997	Maue	8-segment thermal comfort model
1997	Brown	Empirical model of thermal comfort in a car (for Ford)
2003	Fiala	DTS index - dynamic thermal sensation
2003	Guan	Dynamic multi segment Gagge model
2003	Zhang	Berkeley model of thermal comfort
2004	Nilsson	Comfort zone model (in ISO 14505)
2008	Streblow	Linking the Tanabe and Zhang (for Airbus)
2010	Zhang	New Berkeley model of thermal comfort (strictly distinguish sensation from comfort)

The common feature of this models is statistical data processing from questionnaires, where test subjects fill their thermal status perceptions of the environment. Models differ in a way of evaluating thermal comfort such as otherwise asked questions, the different sample of people, different indexes, etc. For the classification of thermal comfort, diagrams can be also used to define the range of physical quantities for which thermal comfort is achieved, like equivalent temperature, operating temperature, effective temperature, standard effective temperature, etc. [3, 14]

2.3 THERMAL COMFORT SCALES

Subjective methods, like the use of rating scales of thermal comfort, have the advantage of being relatively easy to use. They can also successfully be applied when the contributing factors to a response are not fully known. However, these comfort scales have some disadvantages. It is very difficult to suggest accurate wordings styles at different levels of the scales that would clearly capture the thermal comfort. Thermal comfort is indeed a subjective quantity, different people express different preferences. This means that this type of subjective methods require the use of a representative sample of the user population being exposed to the environment of interest, and hence can become quite costly.

2.3.1 BEDFORD SCALE

In 1936, Bedford investigated the comfort of persons engaged in light industrial work. Large numbers of workers were questioned about their feelings of thermal comfort (warmth), and the actual climate was measured. The observations were limited to winter months when the heating was in use. The subjects were tested one, two or three times. The observations were made on nearly 2000 different persons. To be able to use statistics on the data numerical values to the different levels of the sensation, the responses of the workers were classified by seven-point scale shown in Table 2.

Table 2) Bedford scale [18]

Value	Expression
1	Much too warm
2	Too warm
3	Comfortably warm
4	Comfortable
5	Comfortably cool
6	Too cool
7	Much too cool

Bedford moreover states that conditions should be used which as many persons as possible will find comfortable. This means adopting a rather narrow comfort zone for practical purposes. Bedford suggested that a comfort zone should be chosen in which more than 70 % the subjects were comfortable and that in this range at least 86 % of the votes recorded ranged from comfortable cool to comfortably warm. He did not consider with this comfort zone that in the summer people will commonly become more acclimatised to higher temperatures and wear less clothing than in the winter. Temperatures that would be found uncomfortably warm in winter could sometimes be accepted as pleasant in summer. He also proposed two more ways constructing these comfort zones. One was to use those conditions in which not less than 50 % of votes ranged from comfortably warm to comfortably cool. The second way of designing the comfort zone was to take the whole range of temperature in which votes of comfortably cool or comfortably warm, were recorded. [18]

2.3.2 ASHRAE SCALE

In 1971, the studies by Rohles were made on 1600 college students with correlations between comfort level, temperature, humidity, sex, and length of exposure. The thermal sensation scale developed for these studies is called the ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) thermal sensation scale and is shown in Table 3.

Table 3) ASHRAE scale [18]

Value	Expression
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The numerical values in ASHRAE scale are changed compared to the Bedford scale, so the scale ranges from -3 to +3 instead of 1 to 7. This with the intention that the scale should be easier to remember, as it is symmetrical around the zero point, so that a positive value corresponds to the warm side and a negative value to the cold side of neutral. Furthermore, the American standard ASHRAE 55 specifies comfort zones where 80 % of sedentary or slightly active persons find the environment thermally acceptable. Because people change their clothing with the weather and the season, ASHRAE 55 also specifies summer and winter comfort zones appropriate for clothing insulation levels. [18]

2.3.3 PMV SCALE

The PMV (Predicted Mean Vote) scale predicts the mean value of the votes of a large group of persons on the same psycho-physical thermal sensation scale as the ASHRAE. The theory is based on the heat balance of the human body by Fanger from 1970. The human being is in thermal balance when the internal heat production in the body is equal to the heat losses to the environment. The thermal sensation votes were collected from more than 1300 subjects

The PMV index predicts the mean value of the thermal votes of a large group of people exposed to the same environment. Nevertheless, individual votes are scattered around this mean value and it is consequently used to predict the number of people likely to feel uncomfortably warm or cool. The PPD index (Predicted Percentage Dissatisfied) calculates a prediction of the number of thermally dissatisfied people. The PPD predicts the percentage of a large group of people likely to feel too warm or cool, i.e. voting hot +3, warm +2, cool -2 or cold -3 on the 7-point thermal sensation scale. The dependence of PPD on PMV is shown in Figure 9.

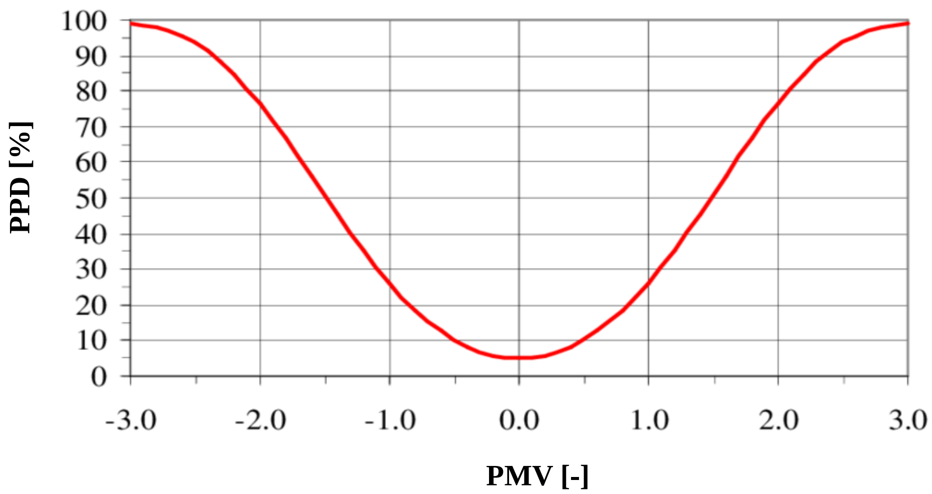


Figure 9) PPD as a function of PMV [20]

The PMV index gives the predicted mean vote of a large group of persons exposed to a given combination of the variables. This mean vote is indeed an expression for the general degree of discomfort for the group as a whole. This makes it difficult to interpret what the value of the PMV, determined in a practical case, can imply on the comfort for a single person. However, all people are different. There will naturally be a certain variance in the thermal sensations of a group of persons exposed to the same environment. The persons of particular interest will be those who are decidedly uncomfortable since it is these dissatisfied persons whom will be likely to complain about the environment. [18]

2.3.4 MTV SCALE

The MTV (Mean Thermal Vote) scale is based on series experiments of total and local heat fluxes from thermal manikins and comparison with thermal sensation votes from 20 subjects exposed to the same 30 different climatic conditions. The individual votes were averaged for each condition and reported as a mean thermal vote. MTV and equivalent temperature for all conditions was subjected to a linear regression analysis by Wyon in 1989 and later by Nilsson in 1997. High correlation coefficients (0,83 and 0,92) were found for segment heat flux and mean thermal vote of subjects for the same body segments. The procedure was repeated for all 16 different body segments for which subjective votes were obtained. The sets of low and high equivalent temperatures are plotted as two profile limits. In this way a comfort profile for the climate over the whole body surface is obtained.

The MTV scale is shown in Table 4. It is similar to the ASHRAE scale. Nonetheless, it uses different word definitions of individual sensations and its main goal is to make it clear to the tested persons. The values -1, 0, +1 are acceptable (comfort) ratings while -2, -3, +2, +3 are unacceptable (uncomfortable). This is not the case with the ASHRAE (PMV) scale, were afterwards an interpretation of the facts that cold and hot are not acceptable while cool and warm are acceptable. The use of the MTV scale is particularly useful when working with thermal manikins, and due to its uniqueness it can bring the most accurate assessment of the tested persons. [18]

Table 4) MTV scale [18]

Value	Expression
+3	Much too hot
+2	Too hot
+1	Hot but comfortable
0	Neutral
-1	Cold but comfortable
-2	Too cold
-3	Much too cold

2.4 EVALUATION

The thermal comfort is assured by the factors that depend on human body thermal interaction, mainly on his ability of thermoregulation. By a definition it is a subjective sensation, which express the level of thermal satisfaction with surrounding environment.

Overall, human thermal comfort is mainly affected by the sensation of air temperature, mean radiant temperature, air velocity, relative humidity, physical activity, clothing thermal resistance and nowadays the solar radiation also begins to be taken into consideration. These factors are independent, but together they contribute to establish the thermal comfort. If one factor suffer changes, then others factors need to be adjusted to maintain the thermal comfort.

In general, thermal comfort can be evaluated using five main approaches, which are human subject responses, sensors, thermal manikins, infrared thermography and CDF models. They are supported by various methods. One of these is human physiology models, which allow predicting the thermal state of the human body and its reaction to surroundings that is particularly useful in CFD simulations. Another is thermal comfort models, which have been constantly developing since 1923 for different areas of use, such as human subject responses, thermal manikin and CFD simulations. And last was the introduction to basic thermal comfort scales such as Bedford, ASHRAE, PMV and MTV. They enable to classify subjective sensation to standardised scales and another statistical processing.

Nevertheless, in 2015, there was still no international standard which allowed to easily assess thermal comfort specific to the vehicle cabin environment. The current state of the art has been inconsistent in methodology. There are often differences in the theoretical approaches of existing studies as well as differences in the experimental methods which assess thermal comfort. Researchers who have studied thermal comfort in vehicles have adopted many concepts and methodological procedures from previously existing thermal comfort literature which was mainly intended for buildings. [21]

3 THERMAL-COMFORT UNITS IN AN AUTOMOBILE

Cabin heating and ventilation systems have become an essential part of personal vehicles and demands for comfortable transport are still increasing. In fact, 85 % of the car trips in Europe are shorter than 18 km and last only up to 30 minutes. Under such conditions, the basic comfort unit cannot usually ensure desired cabin environment and passengers are exposed to thermal stress. For this reason, additional thermal-comfort units help to create the appropriate thermal-comfort environment with consideration of total energy efficiency.

Thus, for a better overall understanding of the thermal-comfort environment in a vehicle, thermal-comfort units, which are used in the automotive industry, will be described. First, HVAC as the almost standard system will be introduced, then three basic types of auxiliary heating system, heated steering wheel, neck-level heating, which is used in convertibles, heated seats and finally ventilated seats. The simplified positions of all described thermal-comfort units are shown in Figure 10. [22]

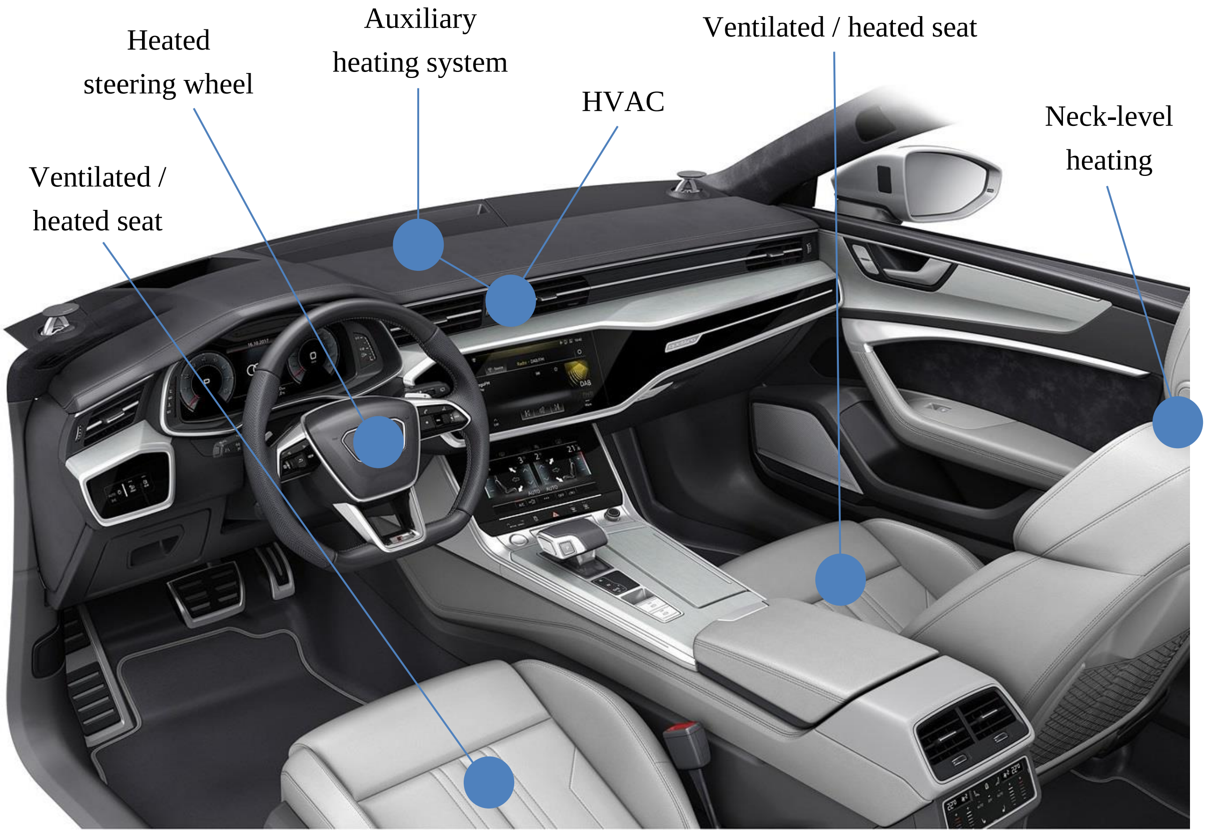


Figure 10) Thermal-comfort units in an automobile [23]

3.1 HVAC

HVAC stands for heating, ventilation, and air conditioning. It provides thermal comfort and acceptable air quality in a passenger cabin. HVAC systems vary in complexity and level of automation depending on the vehicle class. While an economy car requires that a driver manually turn knobs to control the temperature, a higher-end vehicle uses sensors to automatically control not only the temperature but also the humidity and quality of air inside the cabin. Hence, the only main principles are described.

Anyhow, HVAC unit sucks an outside air by its blower through a fresh air control flap. From there, it flows through a dust filter, which removes impurity from the air, such as dust, pollen, etc. Then, an evaporator in an HVAC unit allows cooling the air and on the other hand the heater core its heating. Final air mixture of the required temperature is distributed through flaps and diffusers to the desired locations of the vehicle cabin. If there is the potential of harmful interference from the outside environment, such as driving in a tunnel or traffic jam, a closed circuit with internal recirculation may be activated. Then, the air is sucked almost only from the interior of the vehicle. It is cleaned in the dust filter, treated by the condenser and heater core and then returned to the vehicle cabin. General layout for the HVAC system is shown in Figure 11. [3, 24]

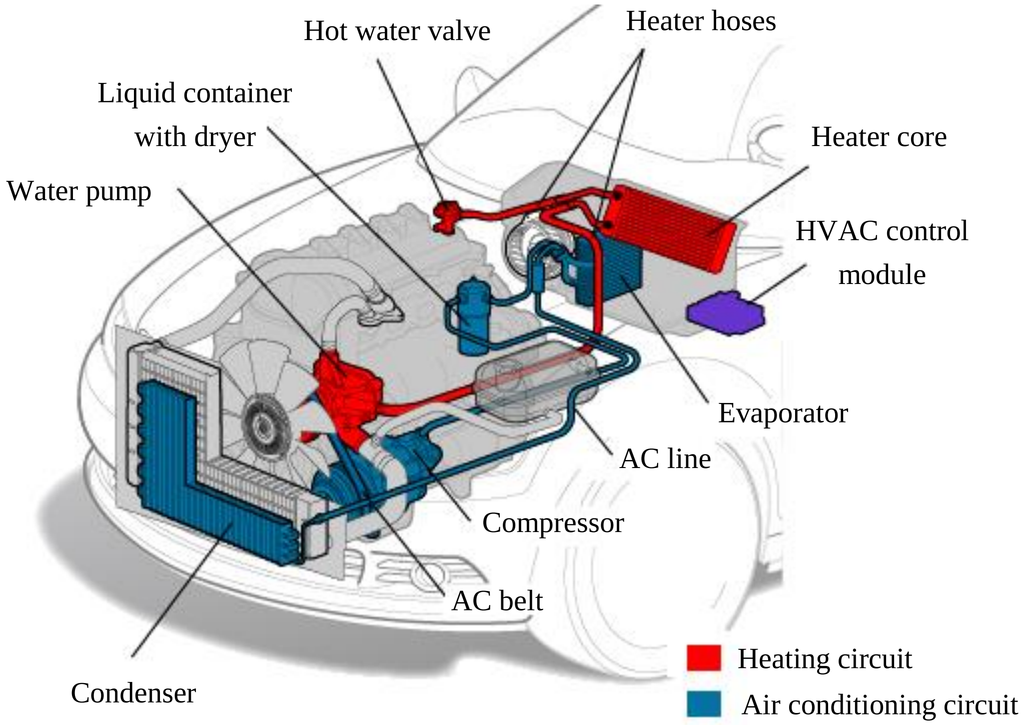


Figure 11) HVAC system [25]

3.1.1 HEATING

Heating in the cabin of a vehicle is provided by a heater core, which is a small radiator used as a heat exchanger mounted in the HVAC unit. It is connected directly to an engine cooling system. Thus, as the engine water pump circulates engine coolant through the cooling system, it heats the heater core to the engine temperature. When heat is desired, the blower motor blows air across the heater core and transfers heat from the engine into the cabin.

To ensure faster warming of the engine to the operating temperature, and so faster warming of the cabin, the engine cooling system consists of two circuits. The small circuit is around an engine block and through the heater core. The big circuit is opened by a thermostat when the engine operating temperature is reached. It means that a coolant flows also through the main radiator, where it transfers the heat to the surroundings and flows back to cool the engine. The whole engine cooling system is shown in Figure 12.

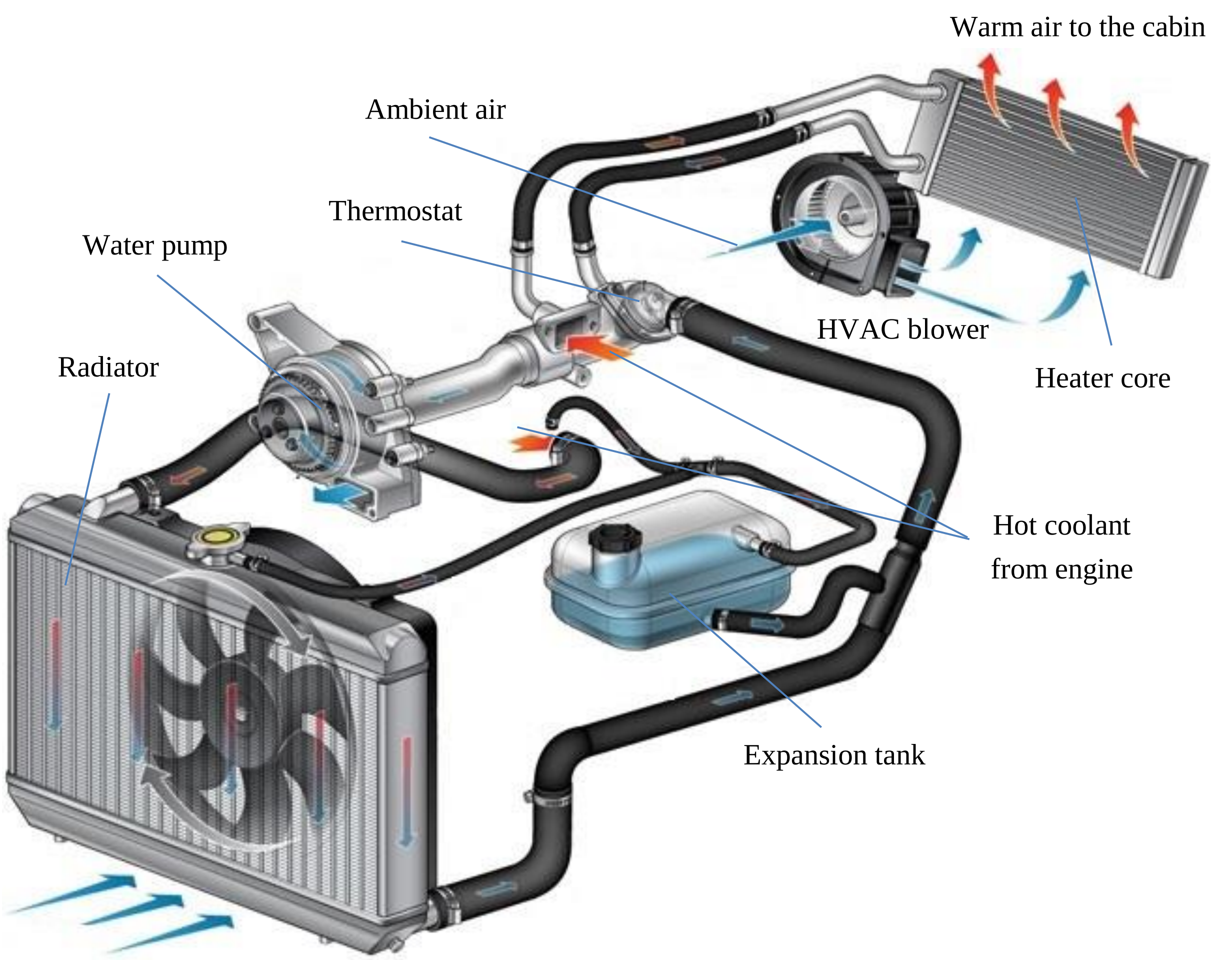


Figure 12) Engine cooling system with the heater core [25]

On newer vehicles, when heat is not desired, the blend door actuators change the flow of air away from, or partially away from the heater core to reduce the amount of heat allowed into the cabin. Older vehicles used a simpler component called the heater control valve. This valve stops the flow of engine coolant into the heater core, and the core is cooled sufficiently to stop production of heat in the cabin.

In the case of an air-cooled engine, a blower forces air over the cylinder's cooling fins to cool it. At the same time, it forces air through an air chamber surrounded the exhaust manifold, which acted as a heat exchanger, scavenging waste heat from the exhaust. After that, it ducts the heated air into the cabin through a control valve.

On the other hand, electric and hybrid cars can be heated by a reverse cycle air conditioning or an electric heater used PTC (Positive Temperature Coefficient), which is basically a resistor that increases its resistance as it heats up. Nevertheless, all mentioned heating solutions can be also supported by auxiliary heating systems, which increase their efficiency. [26, 27]

3.1.2 AIR CONDITIONING

An air conditioning (A/C) unit has the task of cooling, humidification and drying the intake air. It is useful especially if conditions do not allow common ventilation for cooling or if it is necessary to avoid a fogging glass. The principle of air conditioning is based on the removal of heat for cooling the air. It requires a cooling circuit consisting of a compressor, a condenser, an expansion valve, an evaporator and a proper cooling medium, which uses conversions between liquid and gas phase. The function scheme of the cooling circuit is illustrated in Figure 13 and described below.

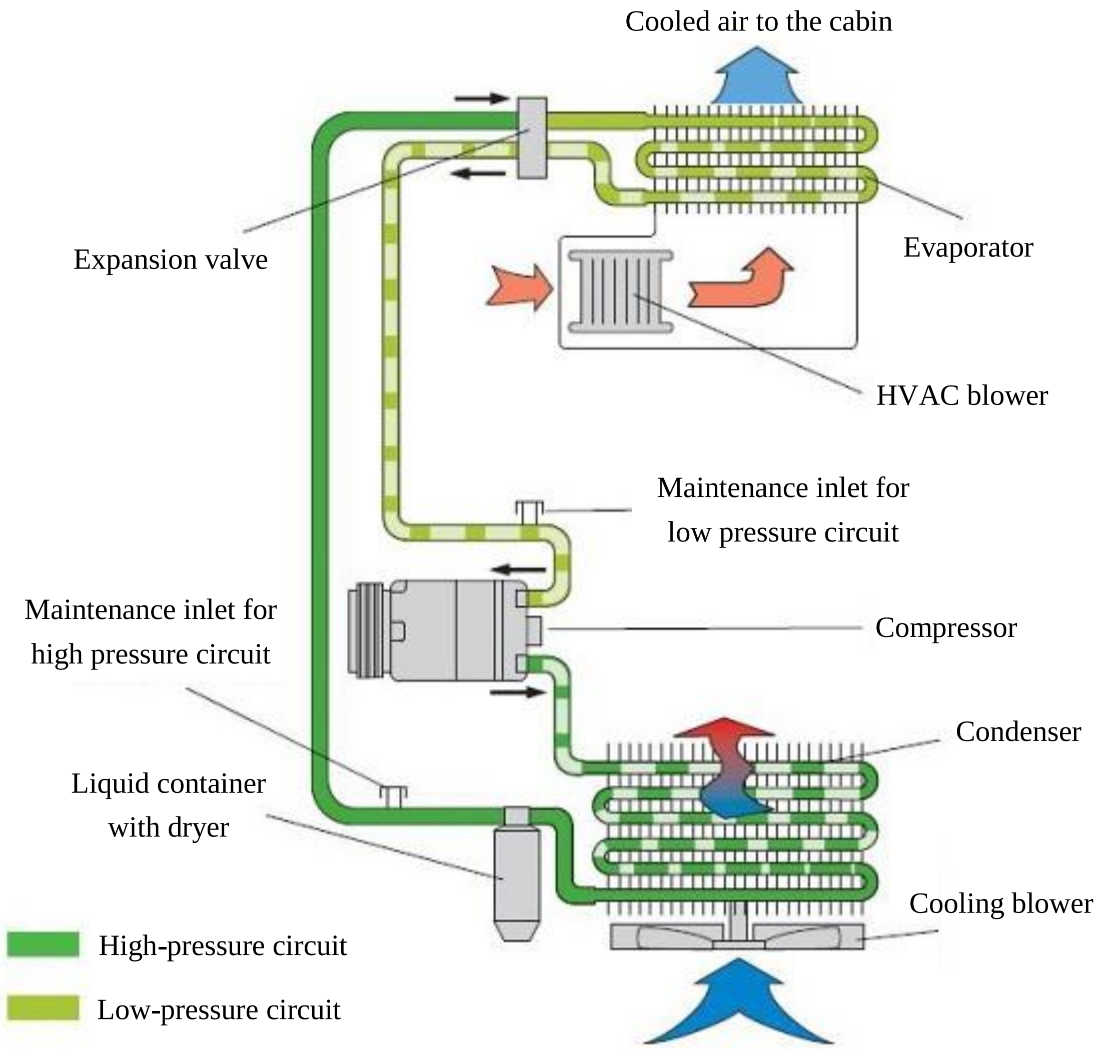


Figure 13) Air conditioning scheme [28]

The compressor draws gaseous refrigerant from the low-pressure circuit. The refrigerant is compressed, thus its temperature increases and it is injected into the high-pressure circuit of the air conditioning system. Then, the refrigerant passes through the condenser, where it transfers part of its heat energy to surroundings. This results in liquefaction of the refrigerant. However, the refrigerant is not always completely liquefied, so prior to the expansion valve, there is a liquid container with a dryer as a buffer vessel. Then, it passes through the expansion valve, where the refrigerant is expanded and turned into the mixture of liquid and steam, thus it transfers its heat energy and it is cooled. In the evaporator, the undercooled refrigerant is changed from liquid to gaseous phase as the evaporator is heated by the heat from the ambient air flowing around its surface. It is because of the boiling temperature of the refrigerant, which is lower than the surface temperature of the evaporator and allows evaporation. Thus, the ambient air is cooled down and further distributed into the cabin. From the evaporator, the gaseous and heated refrigerant flows back to the compressor and the cycle is repeated again.

Refrigerants used in automobile air conditioning are subject to strict environmental and safety requirements. For appropriate function, they have to be non-combustible, non-toxic, non-corrosive and capable of working at low working pressures. At the same time, they have to provide thermodynamic properties such as high latent heat, low liquid-phase density, high gas-phase density, high critical temperature, and boiling temperature lower than an ambient temperature at operating pressure, preferably temperature below 0 °C. Overall, the refrigerants are specified by the standard ISO 13043:2011 Road vehicles — Refrigerant systems used in mobile air conditioning systems (MAC) — Safety requirements.

Nevertheless, the air conditioning also increases a fuel consumption. According to ADAC, when the cabin is cooled down from the outside temperature of 31 °C to 22 °C, the consumption may arise from 0,76 to 2,11 litres per 100 kilometres depending on the driving style and car itself. For instance, the small volume 1,4 litres petrol engine car has the increase of the fuel consumption more than two litres per 100 km higher. On the other hand, the more powerful 2,0 litres diesel engine car with automatic climate control has the increase of the fuel consumption only about 0,7 litres. [3, 28]

3.1.3 MULTI-ZONE CLIMATE CONTROL

Climate control can be described as an automatic HVAC system, it utilizes sensors and an ECU to add additional features to basic vehicle air conditioning. The sensors measure the temperature in and out the vehicle so the system can automatically adjust to keep a proper air distribution, including maintaining a constant cabin temperature setting inside the vehicle irrespective of the temperature outside. The sensors also can measure the air quality for air purification devices, which removes odours and adjusts the humidity before it enters the passenger cabin. An advanced climate control system can also have more than one compressor in the engine bay and also allows dividing the passenger cabin into several temperature independent zones.

- **Dual-zone** climate control has separate controls for the driver and front passenger allowing them to have different temperatures and fan speeds if so desired. This ultimately results in the entire left and right sides of the vehicle with different air conditioning.

- **Three-zone** climate control has separate controls for the driver, front passenger and the rear seat. This allows passengers in the rear seats of the vehicle to have their own settings independent of the dual settings of the front, as it is shown in Figure 14. Controls for the rear seat climate control are usually located at the rear of the centre console. For vehicles such as minivans, large crossovers or SUVs with a third row of seats the second seat settings is usually used for the third row.
- **Four-zone** climate control has separate controls for the driver, front passenger, and the rear seat is divided in two with separate controls for each half allowing four passengers to have their own climate control settings.

Because of the different zones, the air condition vents are located in several areas around the interior of the vehicle. In addition to the regular location of vents on the dashboard, these extra vents can be located at the rear of the centre console (over the rear seat controls), in the b-pillars and in the roof of the vehicle. [29]

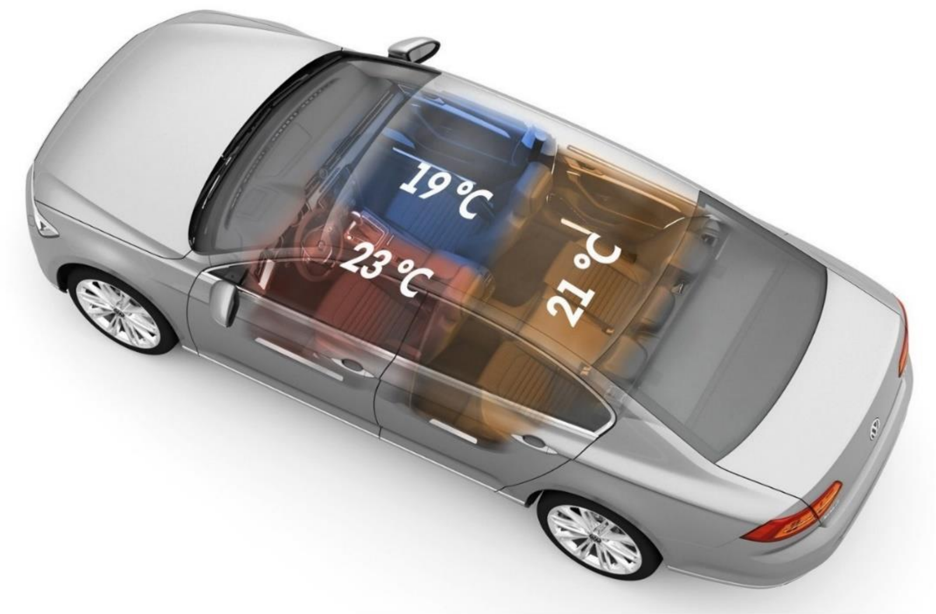


Figure 14) Three-zone climate control [30]

3.2 AUXILIARY HEATING SYSTEM

Auxiliary heating system or commonly called parking heater is an independent heating solution on an engine for automobiles or other means of transport. Essentially, there are two kinds of parking heater. The first one is based on the principle of air heating, which heats the vehicle's cabin. The second one is integrated into the heating circuit of the vehicle, where it heats the coolant, which heats the cabin through the heat exchanger. Both systems are fuel-powered. However, it comes also the new third option, which is based on the principle of water heating as well. Nevertheless, the heat is not provided by fuel but by electricity.

In general, all systems help to reduce engine idling times and provide an efficient working environment even at extreme cold outdoor temperatures, thereby they increase a thermal comfort both for driver and passengers.

3.2.1 AIR HEATER

Air heaters are independent both of the engine and of the vehicle's own heat balance. They heat up the air directly in the heater and bring it into the cabin. Air heaters generate warmth right after they are turned on. They quickly heat the driver’s cabin and ensure evenly distributed temperatures in the cargo and passenger area. They draw in a cool room or outside air, heat this up and then deliver it to the interior of the vehicle. They can be installed as well in the cabin as in the luggage compartment, or under the floor. Therefore, the air heaters are mainly a solution for commercial vehicles of every type. Especially for transporters, personnel carriers and light-duty vehicles as well as for driver's cabins on trucks and motorhome. The function scheme of the water heater system is illustrated in Figure 15 [31, 32].

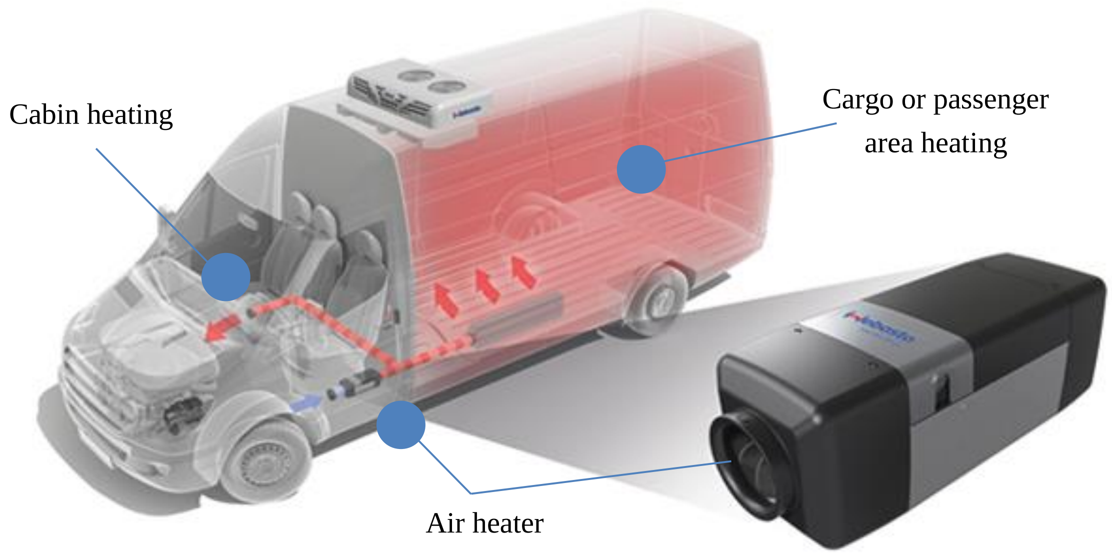


Figure 15) Function scheme of the air heater system [33]

Combustion air from the environment and fuel from the vehicle tank are mixed and ignited in the combustion chamber. Fresh or recirculated air is heated by the thermal energy and fed into the cab. The cross-section of the air heater itself is shown in Figure 16.

Overall, the main benefits of air heater are fast cabin air heating, low electrical power energy and fuel consumption, which is ideal for long heating periods in stationary vehicles. Moreover, the individual configuration of the air distribution, circulating air or fresh air mode, low procurement, installation costs and maintenance and easy to service. [32]

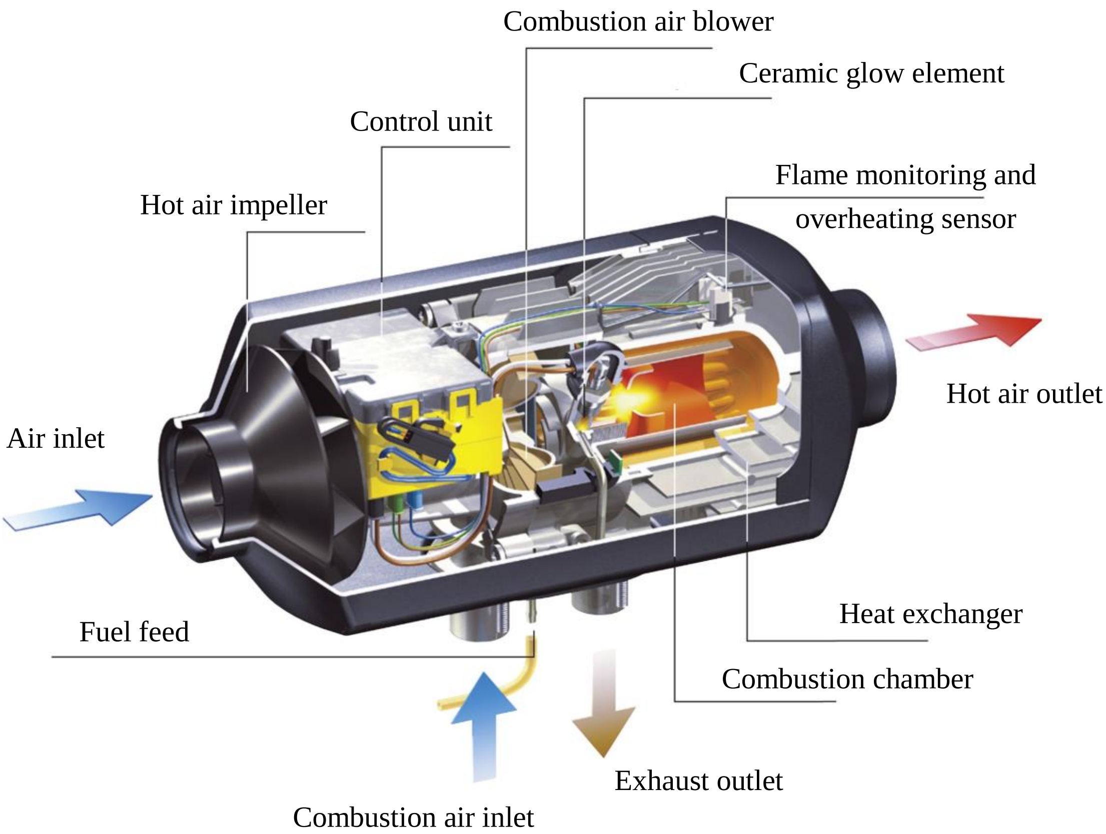


Figure 16) Air heater cross-section [34]

3.2.2 WATER HEATER

The water heater is installed in the engine compartment and simultaneously heats the engine and the vehicle interior. The heater is integrated into the coolant circuit of the vehicle. A circulation pump provides for the uniform heating of the vehicle engine, which produces less noxious emissions after ignition. Compare to cold start, this system can reduce them by up to 50%. At the same time, the vehicle fan blows the warm air flow into the cabin. This solution is used especially in the passenger cars. The function scheme of the water heater system is illustrated in Figure 17 and described below. [35]

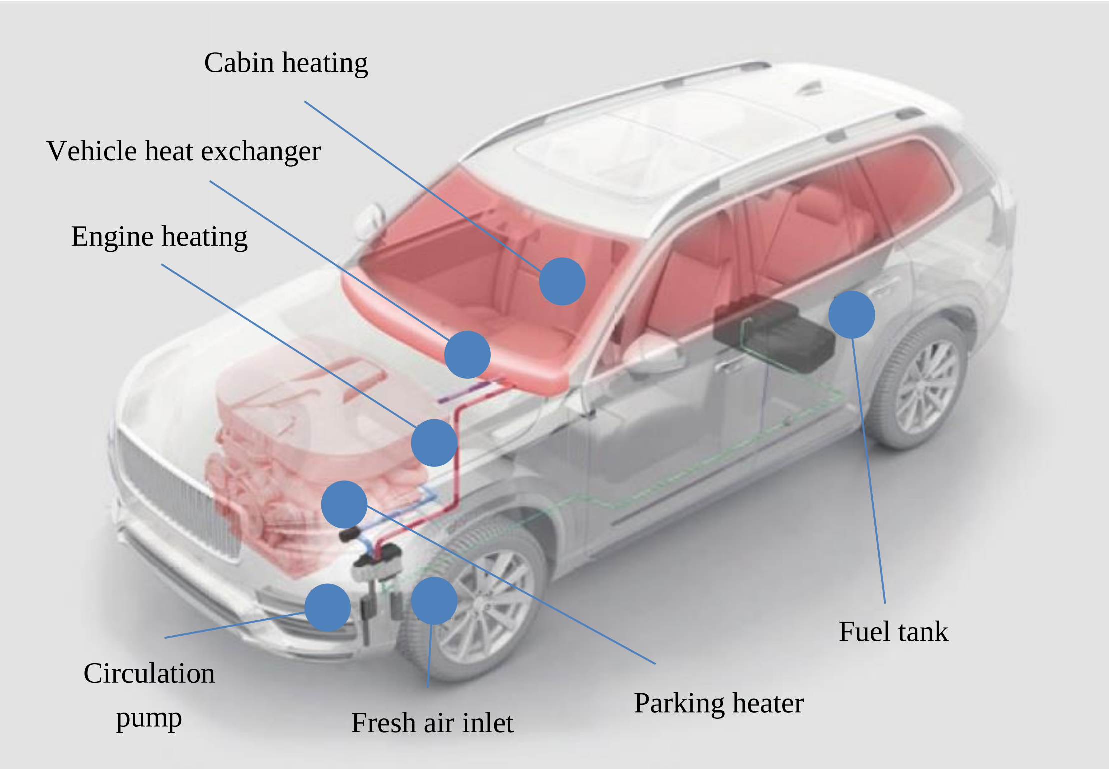


Figure 17) Function scheme of the water heater system [35]

Fuel is conducted from the gasoline tank to the parking heater and the parking heater fan draws fresh air to ignite the fuel-air mix. The circulation pump propels the coolant through the parking heater, vehicle heater, the engine and back. When the coolant is heated up in the parking heater, the coolant gives off the heat in the heat exchanger of the vehicle heater. After that, the heat is conducted into the interior via the vehicle fan. The coolant is transported on to the vehicle engine and heats it up as well. Finally, when the temperature of 80 °C is reached, the heater shuts off, the circulation pump continues to run in order to keep on heating the interior. The cross-section of the water heater itself is shown in the Figure 18. [36]

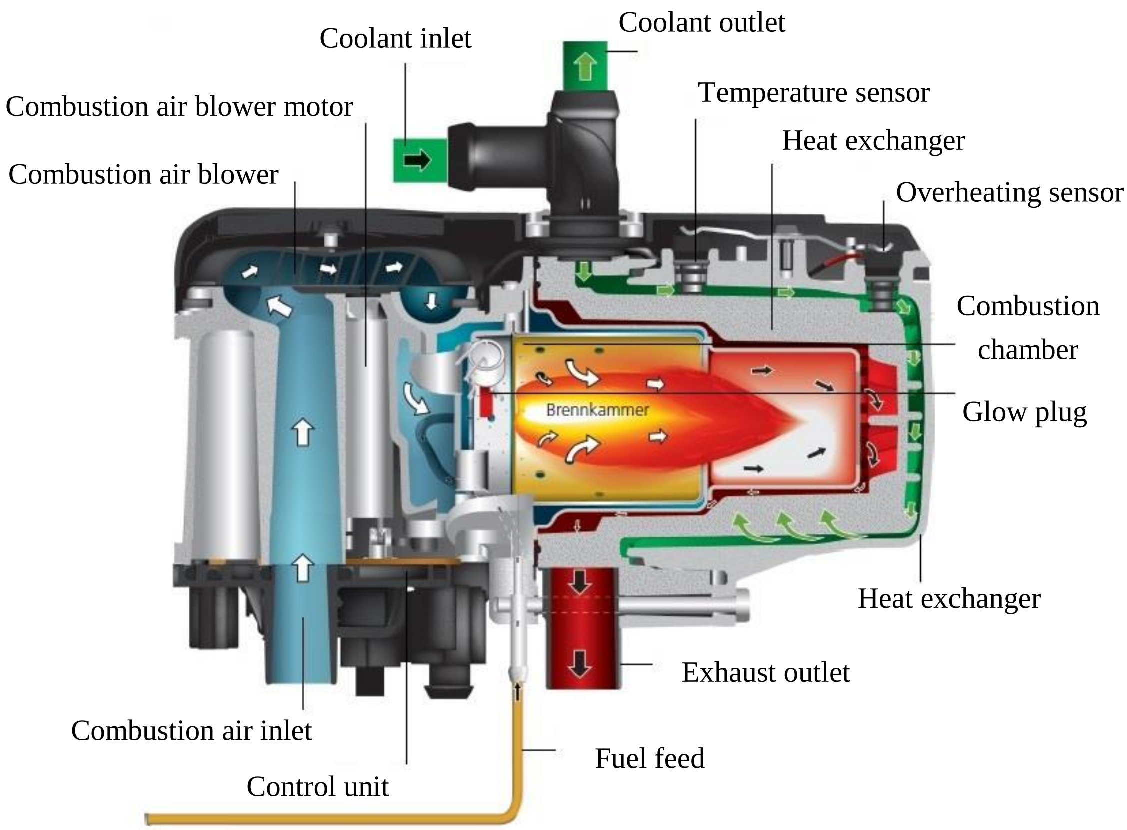


Figure 18) Water heater cross-section [37]

3.2.3 Electric heater

The electric parking heater is integrated into the coolant circuit of the vehicle, similar to the water heater. It means, that a circulation pump provides for the homogeneous heating of the vehicle engine. At the same time, the vehicle fan propels the flow of warm air into the interior and right onto the windshield.

The heater is operated via an electric cable connected to a 230 V power outlet. That makes the parking heater completely emission-free. Thanks to the integrated trickle charge function for 12 V batteries, the car battery is automatically charged throughout the entire duration of an operation. This compensates for the energy from the battery that is required to operate the vehicle fan. Overall, it preserves battery performance and contributes to a secure engine start, which is a major advantage, especially for short distance drivers. The function scheme of the electric heater system is illustrated in Figure 19 and described below. [35, 38]

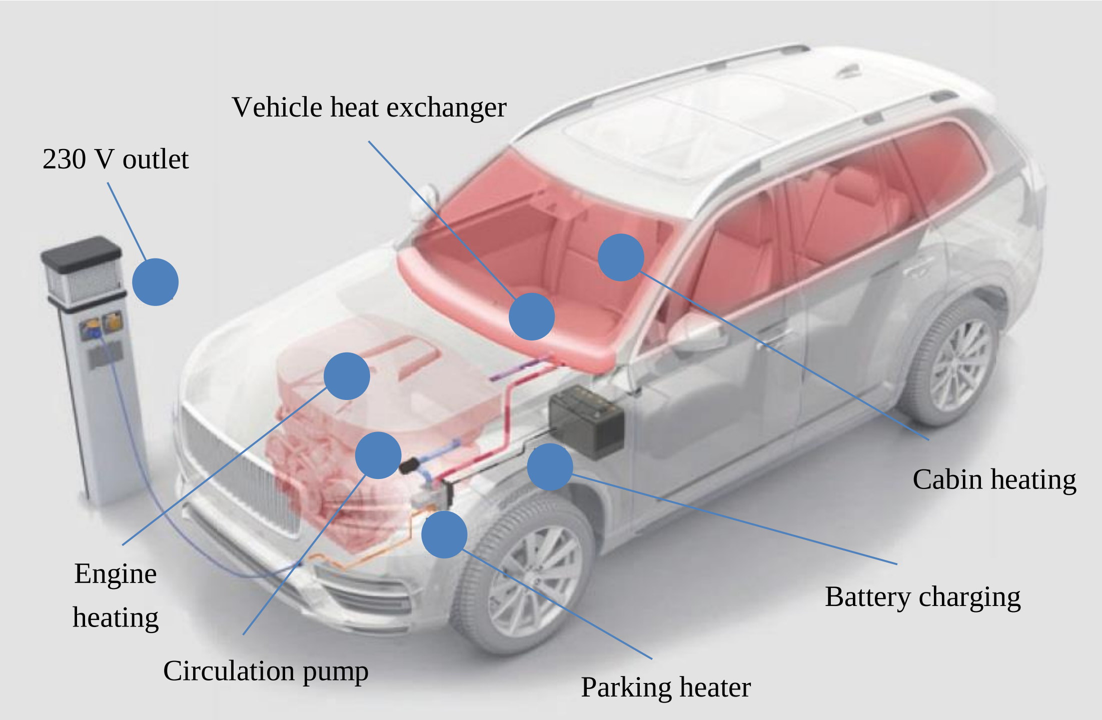


Figure 19) Function scheme of the electric heater system [35]

The car is plugged into the power source of 230 V outlet. The circulation pump conveys coolant through the parking heater, vehicle heater, engine and back. The coolant is heated in the parking heater. The coolant gives off heat to the air in the vehicle heat exchanger. The heated air is disseminated into the interior via the car's own fan. After that, the coolant is transported on to the engine and heats it up as well. Simultaneously, trickle charge function of vehicle battery during heating operation. The electric heater part is shown in Figure 20. Because of its simplicity, it is up to 40 % cheaper than fuel-powered parking heaters. [35]

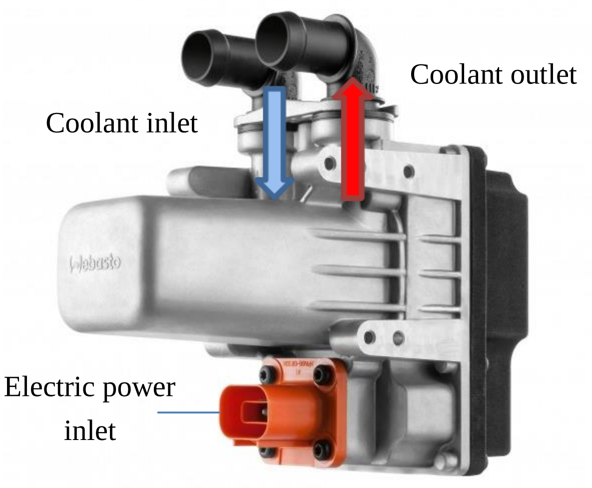


Figure 20) Electric heater part [39]

3.3 HEATED STEERING WHEEL

A heated steering wheel overcomes the ambient low temperature and keeps driver's hands warm. Mostly during winter cold starts, when it is uncomfortable for the driver to put his hands on the cold steering wheel. Especially at the beginning, since a car heating is inefficient and it takes some time to warm the interior and surfaces for the desired temperature. Thermal camera images of the heated steering wheel from the ambient temperature in steps of 60 seconds are shown in Figure 21.

The heated steering wheel is based on a resistance heating wire combined with a felt, which is embedded within a material steering wheel cover. The heated steering wheel mat before the covering is shown in Figure 22. The adjusted temperature is controlled by ECU. Thus, it is simple to design, construct, economical to manufacture, and highly efficient in the accomplishment of its intended purpose. The heated steering wheel mat is mostly combined with a leather cover. [40]

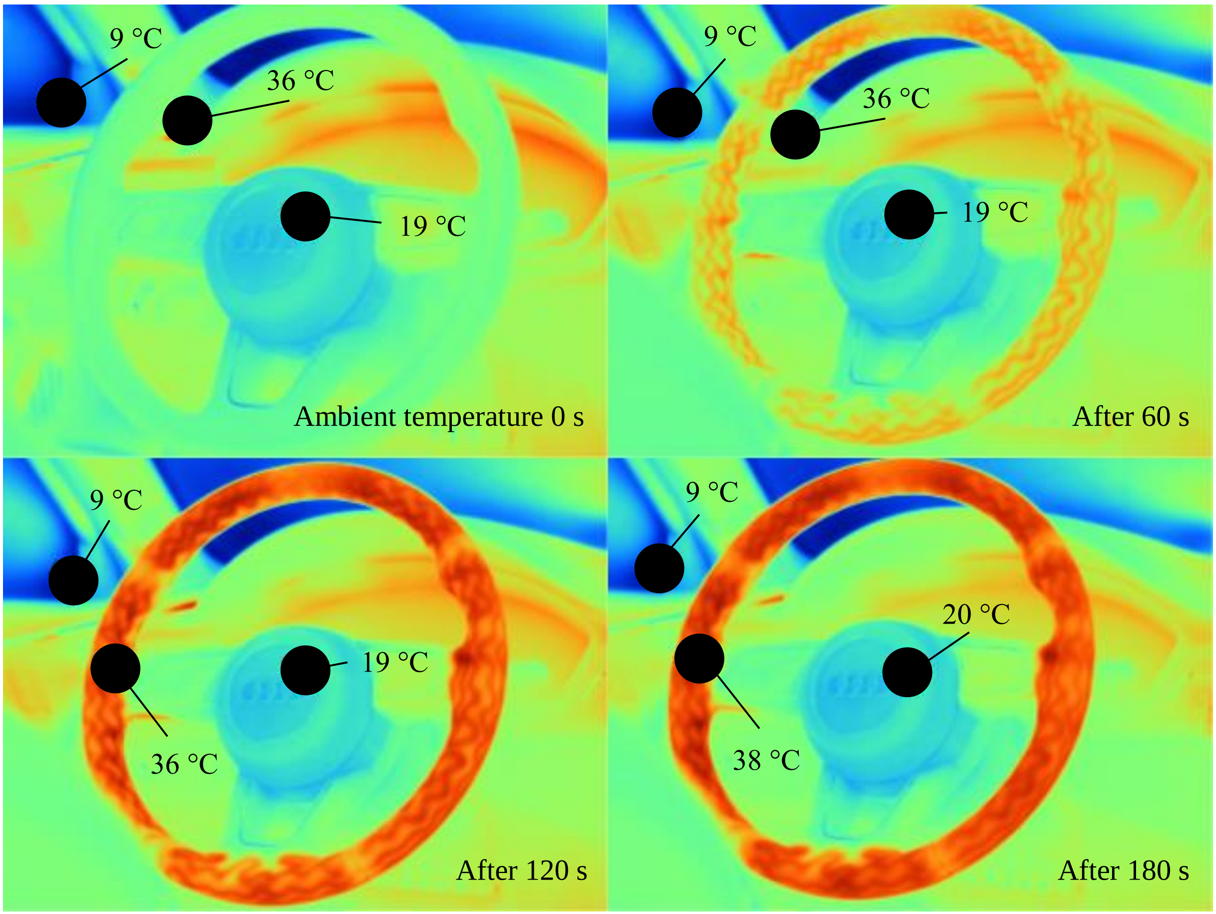


Figure 21) Thermal camera pictures of the heated steering wheel [41]

Figure 22) Heated steering wheel mat [42]

3.4 NECK-LEVEL HEATING

A neck-heating system is mainly known under the registered trademark Airscarf. It is an innovative heating solution used especially in convertibles when a cold wind is blowing over the open cabin. It is able to provide warmth and thermal comfort for the driver and front passenger by warm air flows around the head, shoulders and neck, as it is shown in Figure 23. Thus, it can also prolong the open-air season or rapidly enhance thermal comfort during the winter times by supplementing and supporting the conventional interior heating.

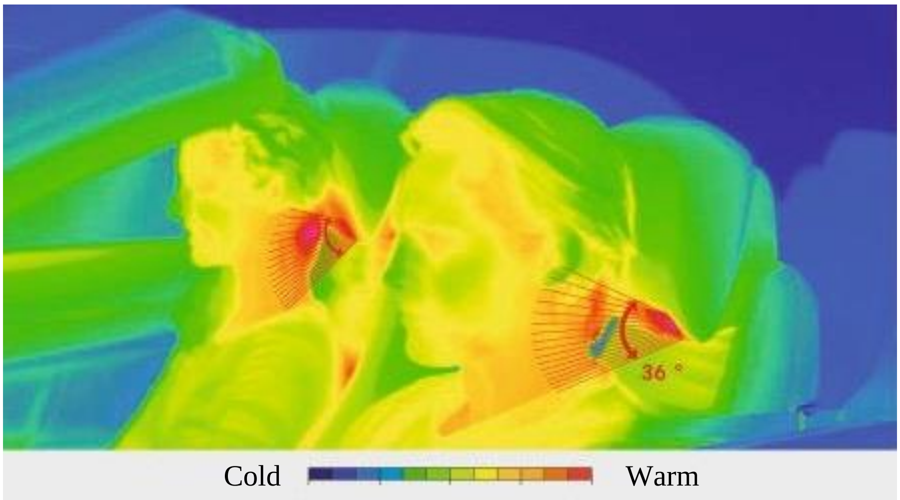


Figure 23) Thermal camera picture of Airscarf [43]

There are two kinds of the neck-level heating system, which are shown in Figure 24 and Figure 25. The first is housed in the seat structure of the backrest between the foam upholstery and the backrest cover. And the second is located in the headrest. Nevertheless, both are based on the same principle. A fan blows the air through the heating element, which is able to heat up in a matter of seconds and provide continuous heat to the needed area. [44, 45]

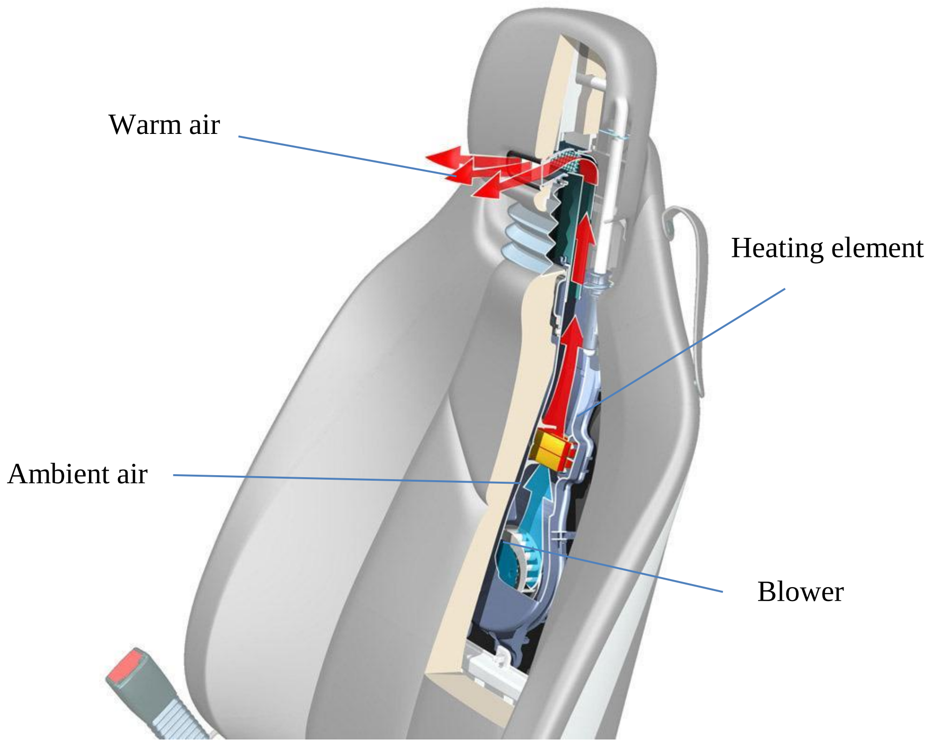


Figure 24) Backrest positioned [46]

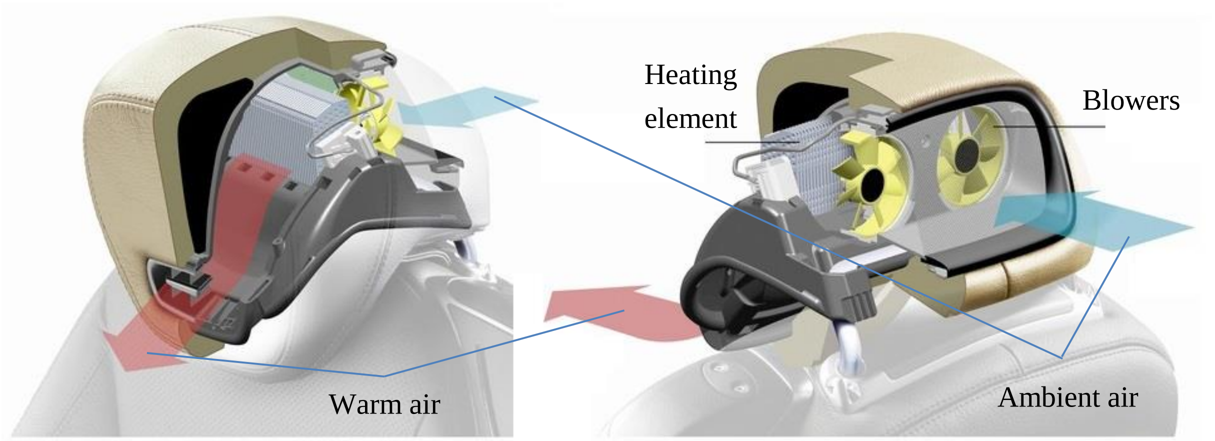


Figure 25) Headrest positioned [45]

3.5 HEATED SEATS

Heated seats, as well as the heated steering wheel, prevent heat losses with the cold surfaces. However, unlike the steering wheel, the contact area of the seat is significantly bigger. Thus, the heated seats have a major impact on the thermal comfort of the driver and passengers during a winter period.

The most common method of heating seats is solved similarly to the heated steering wheel by a copper or aluminium alloy resistance wire. The wire can be sewn to a mat, which is glued directly on the foam surface of the seat, shown in Figure 26. Alternatively, the wire can be stitched to a felt, which is attached to the inner part of a seat cover. Furthermore, the resistance heating wire is supplement by a temperature sensor represented by a NTC resistor, shown in Figure 27. The temperature itself is controlled by ECU.

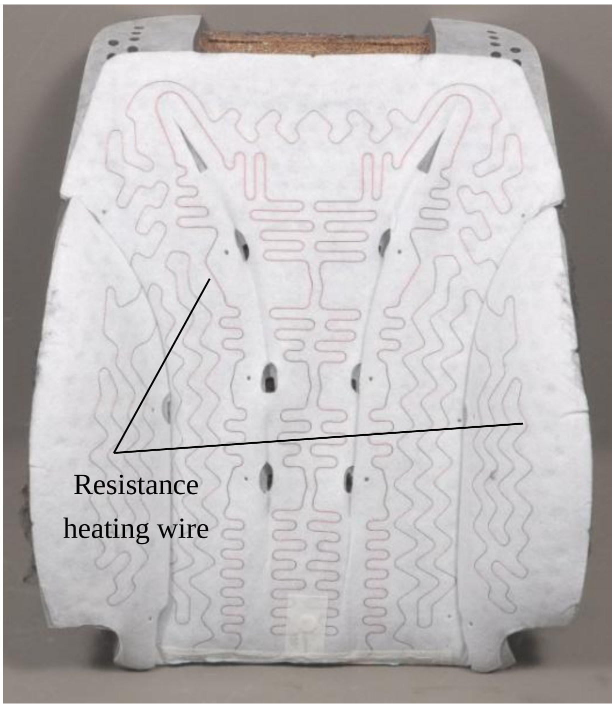


Figure 26) Backrest heating mat

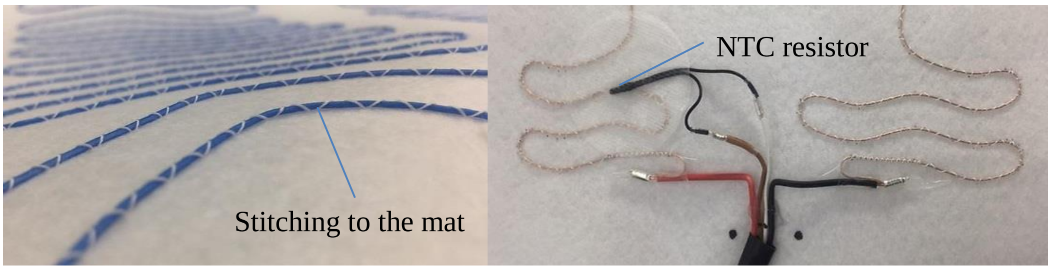


Figure 27) Detailed look to the resistance wire and NTC resistor [47]

The driver or passengers can usually choose between three levels of heating intensity. Typical temperature range on the surface of the heated seat is 30 °C to 32 °C in the first step, 35 °C to 38 °C in the second step and 40 °C to 43 °C in the third step. However, the temperature of a backrest and a cushion can vary by a few degrees. This is due to the different thermal sensation of different parts of the body, in this case, the area of a back and a buttock. Another reason is the different pressure on the seat surface, which results in the different intensity of heat transfer. For example, thermal camera pictures capturing the seat heating in four steps are shown in Figure 28.

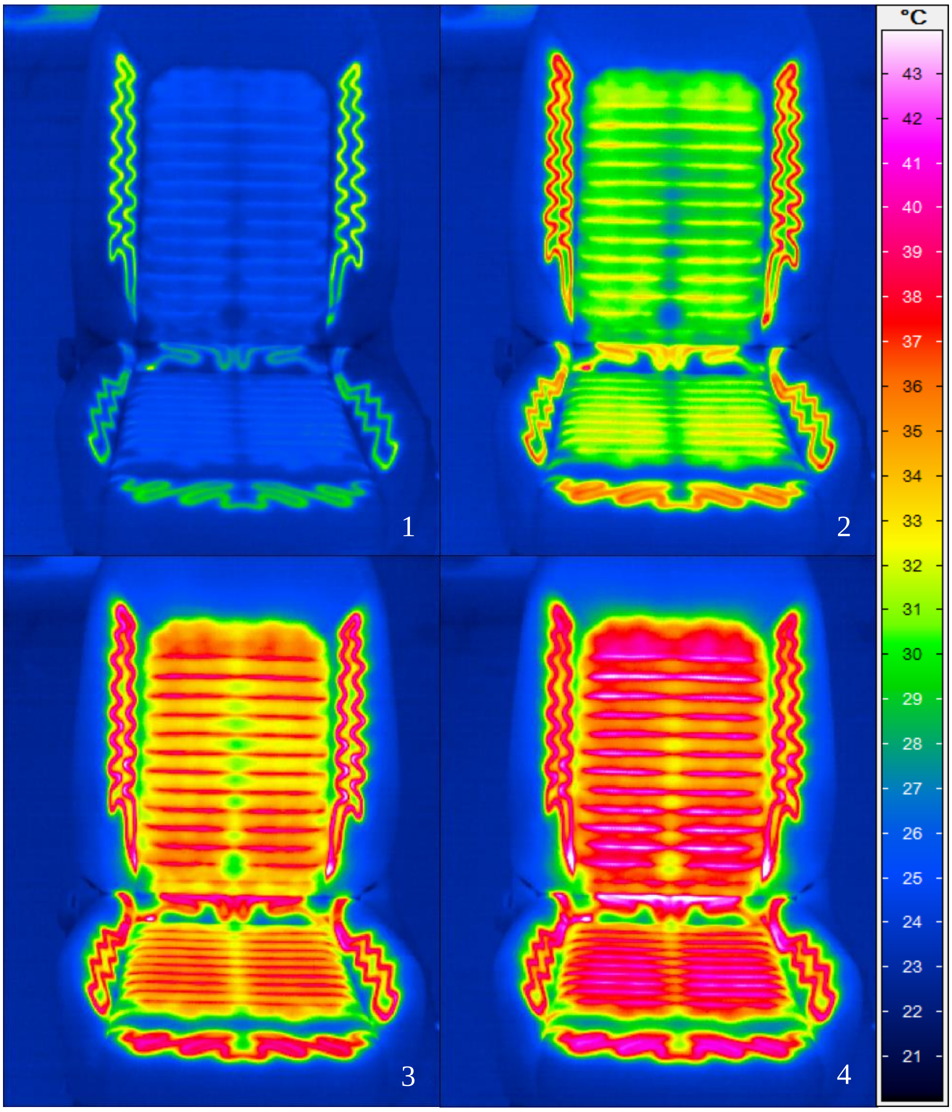


Figure 28) Thermal camera pictures of the heated seat

Overall, it can be said that recommended temperatures on the heated seat are around 34 °C depending on the ambient conditions. On the other hand, the limit contact temperature is 43 °C, which is also determined in standard EN ISO 13732-1:2006 Ergonomics of the thermal environment - Methods for the assessment of human responses to contact with surfaces. Because long-term exposures to temperatures above 43 °C may cause skin burns. [48]

3.6 VENTILATED SEATS

In contrast to heated seats, the purpose of ventilated seats is to cool occupants and provide them satisfactory thermal comfort mainly during hot days in the summertime. They are useful especially at the beginning since the car interior, in particular, the surface of the seats can be very hot and there is no other option how to cool it. Nonetheless, they are also useful for long journeys, when they help to keep convenient thermal sensation.

Under thermal neutral conditions, a person perspires at least 30 g of water vapour per hour. However, in situations when a body cooling is insufficient, it occurs heavier rate of sweating. So, their meaning is to let the heat and the moisture away from the contact area. A great emphasis is also placed on the homogeneity of the ventilation distribution, in order to prevent areas with a different cooling rate. Another crucial topic is the acoustics of ventilation since blowers cause additional noise, which can be heard especially in a well-soundproofed premium class or electric cars. The most common combination of ventilated seats is a cover with perforated leather.

Since the ventilated seats move by a large extent from the premium class to the volume class, most manufacturers use their own approaches and methods to meet their specified parameters. Nonetheless, the final low price of this optional comfort unit is a substantial requirement, especially in the volume class. Thus, the construction of ventilated seats and material choice are extensively distinguished from producer to producer.

However, overall, two types of seat ventilation methods are mostly used according to the air distribution. The push method, which uses blowing the air into the contact area and the pull method, uses extracting the air from the contact area.

Furthermore, the ventilated seats can differ by the number of blowers. It means if there are just one blower per a cushion and one per backrest or there are more in each part. Moreover, by the air distribution through the seat, by the type of the blowers, a radial or an axial, where axial blowers are usually used in combination with several pieces by the contrast of radial blowers. Additionally, by the position of blowers, if they are attached to the skeleton of the seat or embedded directly to the foam from the bottom or from above. For example, the positions of the radial blower are shown in Figure 29, where the left side blower is used for blowing mode and is embedded directly to the foam and the right side blower is used for blowing mode and is attached to the skeleton of the seat. And finally, they can differ by the location of blowers, where they are specifically placed. For example, in use of one blower, if it is in the front or back of the cushion, in the centre or on the side etc.

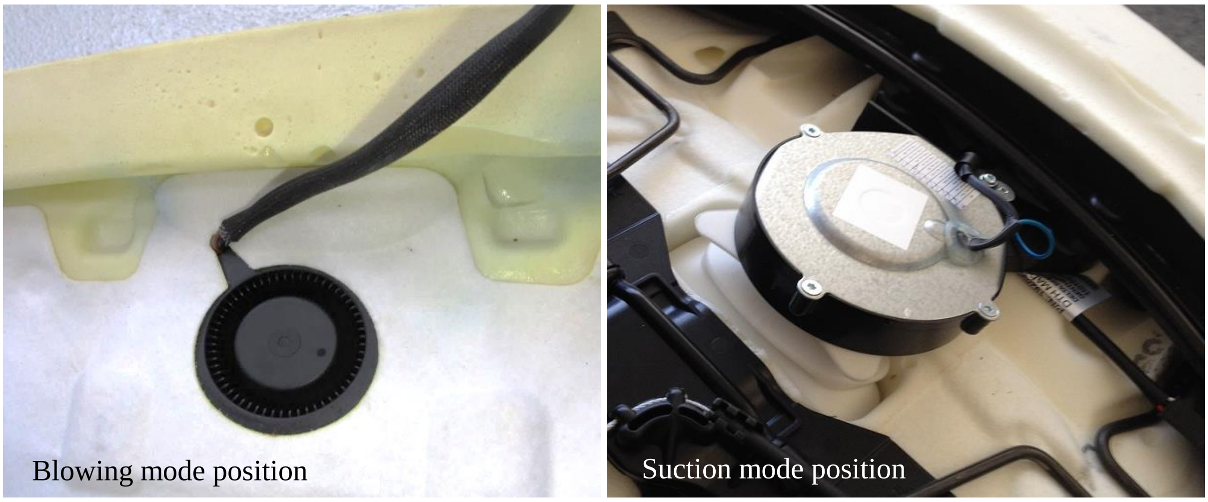


Figure 29) Radial blower positioning

For instance, one solution of the ventilated seat is shown in Figure 30. It is the premium-class ventilated seat with four axial-blowers in the cushion and two axial-blowers in the backrest embedded to the foam from above. [22]

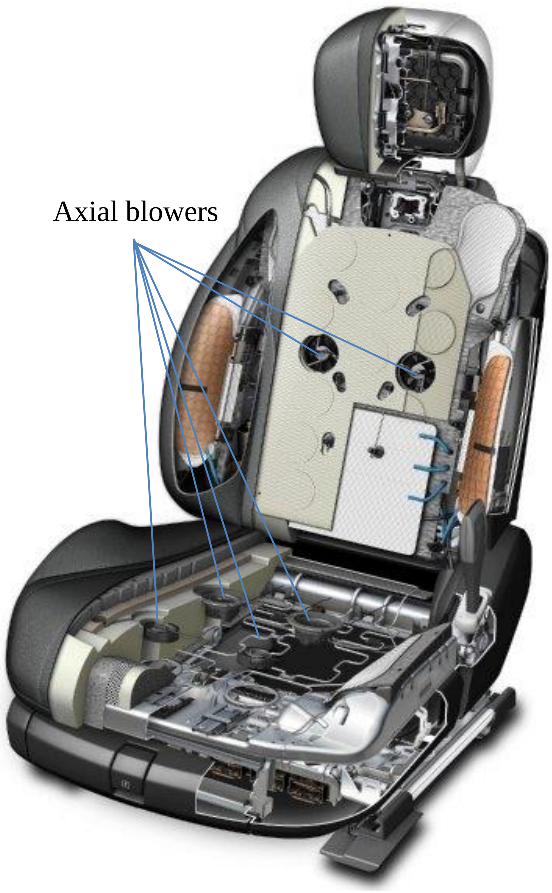


Figure 30) Cross-section of a ventilated seat [49]

3.7 EVALUATION

The microclimate in the car cabin considerably affects the thermal comfort of a driver and passengers. In the interior of the vehicle is emphasized on thermal comfort not only for reasons of convenience but also for safety. Scientific studies in the past have shown the impact of inappropriate working environments on fatigue and attention, which also applies to driving the car. Systems, which provides a suitable microclimate in the cabin, become one of the important safety features of the car. Especially during long journeys, when the appropriate microclimate is necessary for keeping the driver concentrated.

The overall cabin microclimate is formed on the basis of heat transfer as between the exterior and interior of the cabin as in the cabin itself. It means inside the interior between the driver and passengers and surroundings, which includes effect both from the ventilation system and all other thermal-comfort units. Due to the variety of operating conditions of the vehicle, the microclimate in the cabin is influenced by a number of factors such as external influences, i.e. weather, the orientation of the car towards the sun and daytime. Furthermore, it is a car size, glazing area and colour of the vehicle itself. Next, the number of people inside the cabin, who produce additional heat and humidity. And finally, the mentioned thermal-comfort units.

Anyway, today, the development of thermal-comfort units in the cabin is focused on two primary objectives: to provide a comfortable environment for all operating and climatic conditions, even the extreme weather conditions and to reduce energy consumption, which means to increase the overall efficiency of the thermal-comfort system as a whole.

For instance, as the seat has direct contact with the occupant it has much higher thermal conductivity compared to air, which is a poor conductor. With direct contact cooling or heating load per person could be reduced to less than 700 Watts compared to 5,000 W to heat or cool the entire cabin.

From this reason, it is crucial to focus on the local thermal-comfort units, such as heated and ventilated seats, heated steering wheel and neck-level heating, which quickly and directly affect the driver and passengers comfort. Together with the auxiliary heating system, which prepares the vehicle before it was started, and the HVAC unit, that provide ambient thermal-comfort conditions, they are the way how to secure, as it was said, well thermal-comfort conditions, while reducing the energy compulsion. Which is in these days a pivotal issue, especially for hybrid and electric cars. [3, 50]

4 MEASUREMENT METHODOLOGY

As it was said at the end of Chapter 2 Thermal comfort, there was no specific standard for this kind of thermal comfort measurement. Therefore the measurement methodology was based on the long-term experience of the climate chamber and thermal comfort laboratories at BUT FME (Brno University of Technology, Faculty of Mechanical Engineering) as well as it was adapted to their possibilities.

The object of the study was a ventilated car seat. For comparison, it was also examined a standard seat to be better seen the difference between default and advanced version of the seat. Nevertheless, the primary task was to locally inspect the ventilated seat from the point of thermal comfort using two methods of air distribution – blowing and suction.

In this chapter will be introduced the measured data processing, all used measuring instruments, followed by the description of both measured seats. Then, it will be continued with whole measurement description including the measurement layout, the measurement procedure, the questionnaire survey and ended by tested person information.

4.1 MEASURED DATA PROCESSING

Thermal comfort is the subjective quantity of a person feeling, therefore likewise smell and bitter tests it does not belong to the metrology area. It is based on the group of trained or certified persons (depends on the application), which assesses their impression on the given condition subjectively

The measurements are usually assessment by questionnaire survey, which tested persons filled out during the measuring. In that case, it was supported by an objective quantity of the contact and ambient temperatures together with humidity. Which means, for these applications, combined uncertainty is not taken into the consideration because the gained data is just the record of the contact and ambient conditions with the scaled feelings of the person.

Anyway, since the measurement was repeated, a statistical evaluation could be applied by using the mean value and the sample standard deviation to obtained temperatures and humidity. Where humidity was appraised by calculated specific humidity. Other data, especially the subjective from the questionnaire survey, was evaluated only by using the mean value. [51]

4.1.1 Sample standard deviation

The sample standard deviation was calculated as follow equation [52]:

$$s = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} (x_i - \bar{x})^2}, \tag{1}$$

where s is the sample standard deviation, x_i are sample values, $\bar{x}$ is the mean value, and N is the number of observations.

4.1.2 Specific humidity

Specific humidity was calculated as follow equations [53]:

$$q = 0{,}662 \cdot \frac{\frac{RH}{100} \cdot P}{p - \frac{RH}{100} \cdot P} \cdot 1000, \tag{2}$$

where q is specific humidity in g/kg d.a., RH is relative humidity in %, P is partial pressure of water vapour in Pa, and p is atmospheric pressure in Pa.

Partial pressure of water vapour was calculated as follow equation:

$$P = \exp\left(23{,}58 - \frac{4044{,}2}{235{,}6 + T}\right), \tag{3}$$

where T [°C] is temperature.

4.2 Measuring instruments

During the measurement, it was used following instruments to simulate the ambient conditions and capture the data from measuring. It was the climate chamber, Testo measuring device, Sensirion sensors and Mahöle measuring mat.

4.2.1 Climate chamber

The climate chamber is capable of simulating external atmospheric conditions. It allows to test both lifetime and functionality of automobiles, vehicle cabins, solar systems, cooling equipment, heat pumps and other industrial products as well as to examine thermal comfort by thermal manikin or by people respond in various climatic conditions.

BUT FME has been equipped by the climate chamber since 2013 from Angelantoni Industrie S.P. A. The dimensions of this chamber are (5 x 8,85 x 3,8) m (width x length x height), thus combine with exhaust system it is also suitable for car engine-running testing, which is demonstrated in Figure 31. In climate chamber, it is possible to regulate the air temperature and its humidity with optional solar radiation simulation. Nevertheless, the chamber does not have the wall temperature adjusting and the air flow rate controlling. However, the required air rate can be achieved using additional devices installed inside the climate chamber. Overall technical parameters of the climatic chamber are listed below.

- Temperature range (with solar simulation) from -10° to +50 °C
- Temperature range (without solar simulation) from -40° to +85 °C
- Temperature change rate (IEC 60068-35-5) ±1 °C
- Relative humidity range (with solar simulation) from 30 to 60 %
- Relative humidity range (without solar simulation) from 30 to 95 %
- Moisture stability ±5 %RH
- Solar simulation up to 10 kW, 1000 W/m^2
- Air exchange during ventilation 3000 m^3/h
- Air exchange during operation 300 m^3/h
- Internal chamber volume 152 m^3 [54]

Figure 31) Climate chamber [54]

4.2.2 TESTO MEASURING DEVICE

Testo is a multifunctional instrument for analysing ambient air. Its application options vary depending on the type of probes connected, which are shown together with Testo measuring device in Figure 32. It is capable of measuring flow velocity, temperature, humidity, absolute pressure, but also turbulence and CO_2. Some types of probes are also suitable for measuring in air ducts. It can also be estimated using wireless radio probes, and at the same time the device can evaluate and show data from up to three radio receivers at the same time. The measurement results are documented using the ComSoft program on the computer. The program can display a graph and a table of values. During the measurement, Testo 435-4 and radio handle with humidity module were used to measure the ambient temperature and humidity inside the climate chamber. Basic technical parameters of the used Testo measuring device are listed below. [55]

- Type Testo 435-4 with compact professional humidity module
- Module number 0636 9736
- Temperature (by NTC) measuring range from -20 °C to +70 °C
- Accuracy ± 0,3 °C
- Resolution 0,1 °C
- Humidity (by capacitive) measuring range from 0 to 100 %RH
- Accuracy ±2 %RH
- Resolution 0,1 %RH [56]

Figure 32) TESTO 435 with additional measuring probes [55]

4.2.3 SENSIRION SENSORS

The digital pin-type relative humidity sensor from SHT7x series uses a capacitive sensor element for measuring relative humidity, while the temperature is measured by a band-gap sensor. The sensors integrate sensor elements and signal processing in a compact format and provide a fully calibrated digital output. The design of the SHT7x series allows the best possible thermal coupling to the environment and decoupling from potential heat sources on the main board. Its assets are the individual precision calibration, the on-chip calibration memory, and the digital two-wire interface. During the measurement, the SHT7x sensors were used to measure the surface temperature and humidity. The SHT7x humidity sensor series is shown in Figure 33. Basic technical parameters of the used sensors are listed below.

- Type SHT71
- Dimensions (19,5 x 5,08 x 3,1) mm
- Temperature measuring range from -40 °C to +125 °C
- Accuracy ± 0,4 °C
- Humidity measuring range from 0 to 100 %RH
- Accuracy ±3 %RH [57]

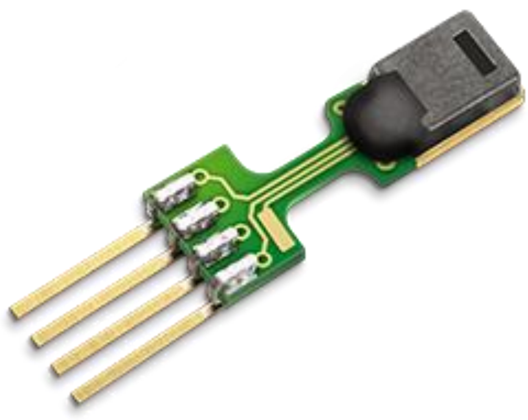


Figure 33) Sensirion temperature and humidity sensor [57]

4.2.4 MAHÖLE MEASURING MAT

Measuring mat Symbiscan TS2e is a data acquisition system from Mahöle Messtechnik, which can acquire temperature allocations in gaps and on surfaces. The system measures and displays up to 512 temperature sensors, which are situated in two 16 x 16 sensor matrixes, shown in Figure 34. Anyway, the matrix can have the size of few centimetres till several metres large. During the measurement, the measuring mat was used to measure heat flux on the ventilated seat. Basic technical parameters of the used measuring mat are listed below.

- Type TEM-4e 16 x 16 Matrix
- Measurement range (48 x 48) cm
- Temperature range from -25 °C to +80 °C
- Acquisition speed ca. 1,5 sec
- Resolution ± 0,01 K
- Accuracy ± 0,3 K [58]

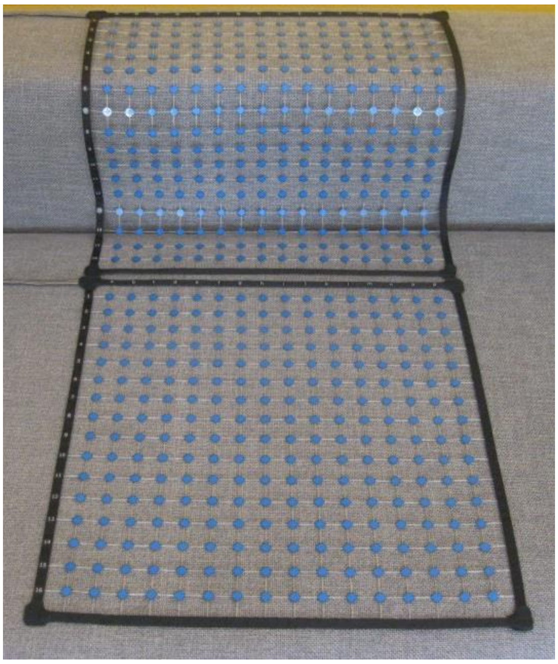


Figure 34) Sensor matrixes [58]

4.3 MEASURED SEATS

For this measurement, it was used two front car seats. A control seat without any comfort function for determination of default conditions and a ventilated seat with the adjustable mode of blowing or suction both in backrest and cushion. That, it could be seen the difference between standard and ventilated seat as well as the difference between particular modes. Unfortunately, because of limited facilities of the laboratory measuring equipment, it could not be used exactly the same seats with the same cover material. Nevertheless, the primary objective of this measurement was to expose the difference between blowing and suction mode with consideration of local thermal comfort. So for the assessment of the detection between the contrast of standard and ventilated seat, the use of different seats was suitable enough.

4.3.1 CONTROL SEAT

As a control seat, it was used a basic front seat from a volume car without any comfort function. It was equipped with four sensors measuring temperature and humidity. Two sensors were placed on the backrest, and two on the cushion. Sensors on the backrest were positioned to represent the middle back and the lower back area. On the cushion, the positions represented the buttock and thigh area. Measuring scheme of the ventilated seat is shown in Figure 35. Cover of this seat was from regular fabric using in this segment.

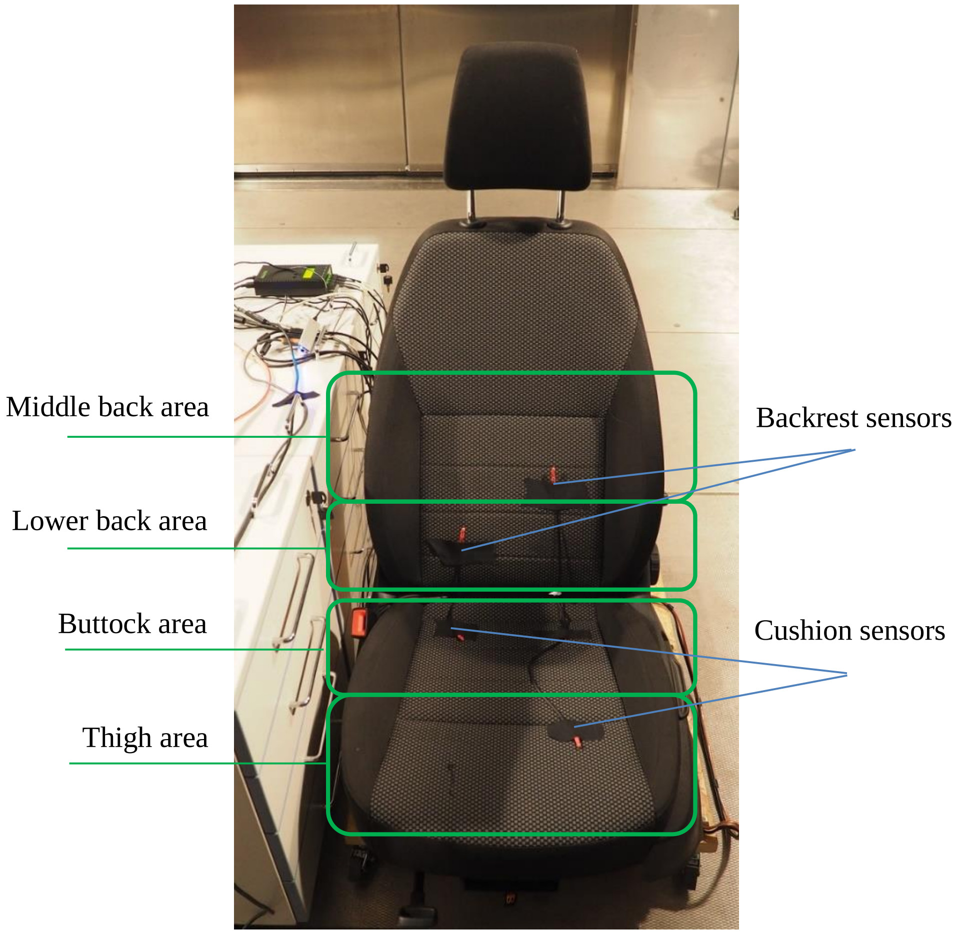


Figure 35) Measuring scheme of the control seat

4.3.2 VENTILATED SEAT

For a ventilated function it was used specially modified front seat, which allows both blowing and suction mode with the separated regulation of backrest and cushion. To be secured same conditions for both air-distribution directions, it was used separated blower for blowing and separated for sucking, where the blowers were set to deliver the same amount of air volume through the seat. In total, it was used two blowers for backrest and two for cushion, altogether four. It was used the same type of radial blowers as it is used in the series production of ventilated seats. The direction of ventilation was controlled by an electro motoric valve on which both blowers were attached, it can be seen in Figure 36. Besides, part of the ventilated seat was the remote control, shown in Figure 37, that tested persons could handle the settings of the seat. It comprised the direction of ventilation, which was set at the beginning of the test, and the intensity of ventilation in three steps, which could be changed during the test and was also separated for backrest and cushion.

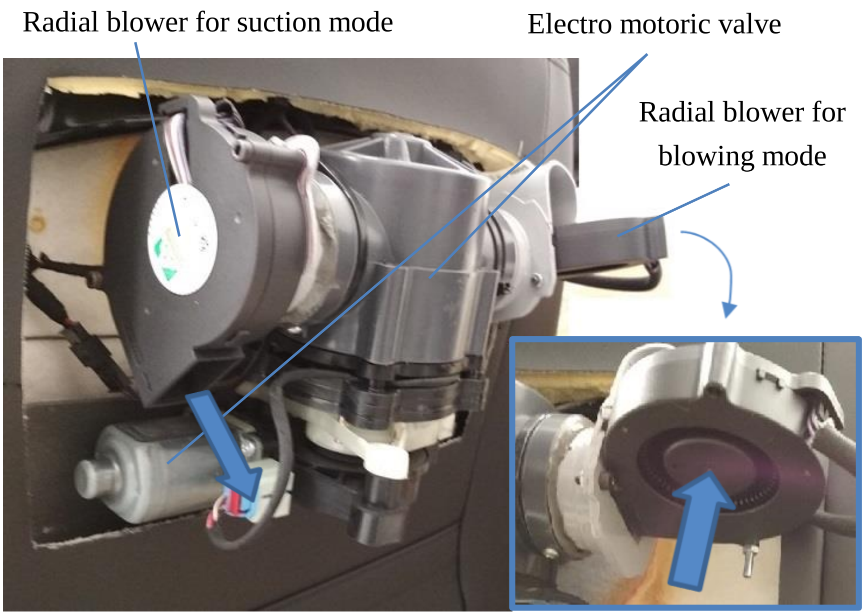


Figure 36) Back-side view of the backrest ventilation system

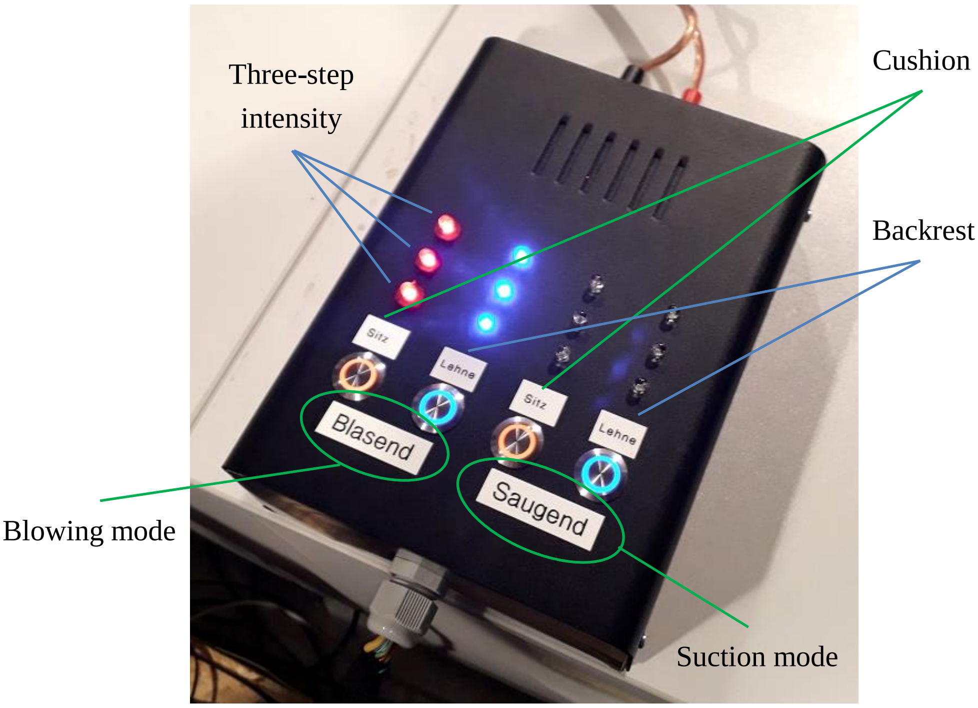


Figure 37) Remote control

The ventilated seat was equipped with four sensors measuring temperature with humidity, as the control seat, plus two Mahöle sensor matrixes for heat flux. Two sensors and one sensor matrix were placed on the backrest, as well as on the cushion. Again, sensors on the backrest were positioned to represent the middle back and the lower back area. Similarly, it was used sensors from the measuring mat just for two location bounded in two squares of sensor-borders 3-7 (vertically) e-l (horizontally) and 9-16 e-l, where the sensor 16-a was represented by the down-left corner. On the cushion, the positions represented the buttock and thigh area. Measuring mat were sensor-borders of 10-15 e-m for buttocks and 4-8 d-g together with 4-8 k-n for thigh, where the sensor 1-p was represented by the front-left corner. Measuring scheme of the ventilated seat is shown in Figure 38. As it can be seen, this seat was modified from the higher optional version of volume car, which contains perforated leather.

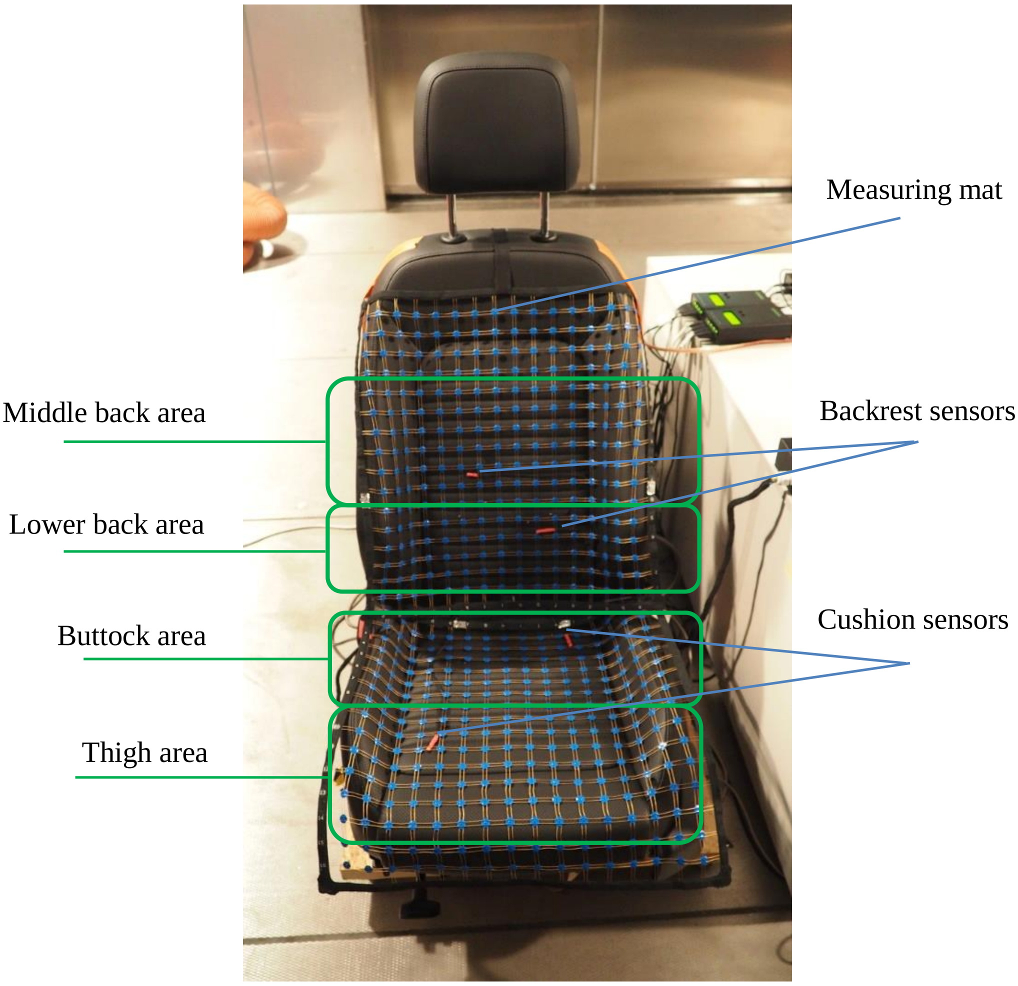


Figure 38) Measuring scheme of the ventilated seat

4.4 MEASUREMENT DESCRIPTION

In this part, it will be introduced and described the measurement layout in the climate chamber, the measurement procedure, used questionnaire with representative scales, and basic information of tested persons.

4.4.1 MEASUREMENT LAYOUT

The layout of the measurement is graphically represented by Figure 39 and Figure 40. The measurement in the climate chamber consisted of the control and ventilated seat, the remote control of the ventilated seat, four sensors on each seats, the measuring mat, Testo measuring device with a probe for measuring ambient conditions, a permeable textile wall, an area for acclimatisation, and a screen with a time counter, that tested persons knew when they had to fill out the corresponding row in the questionnaire.

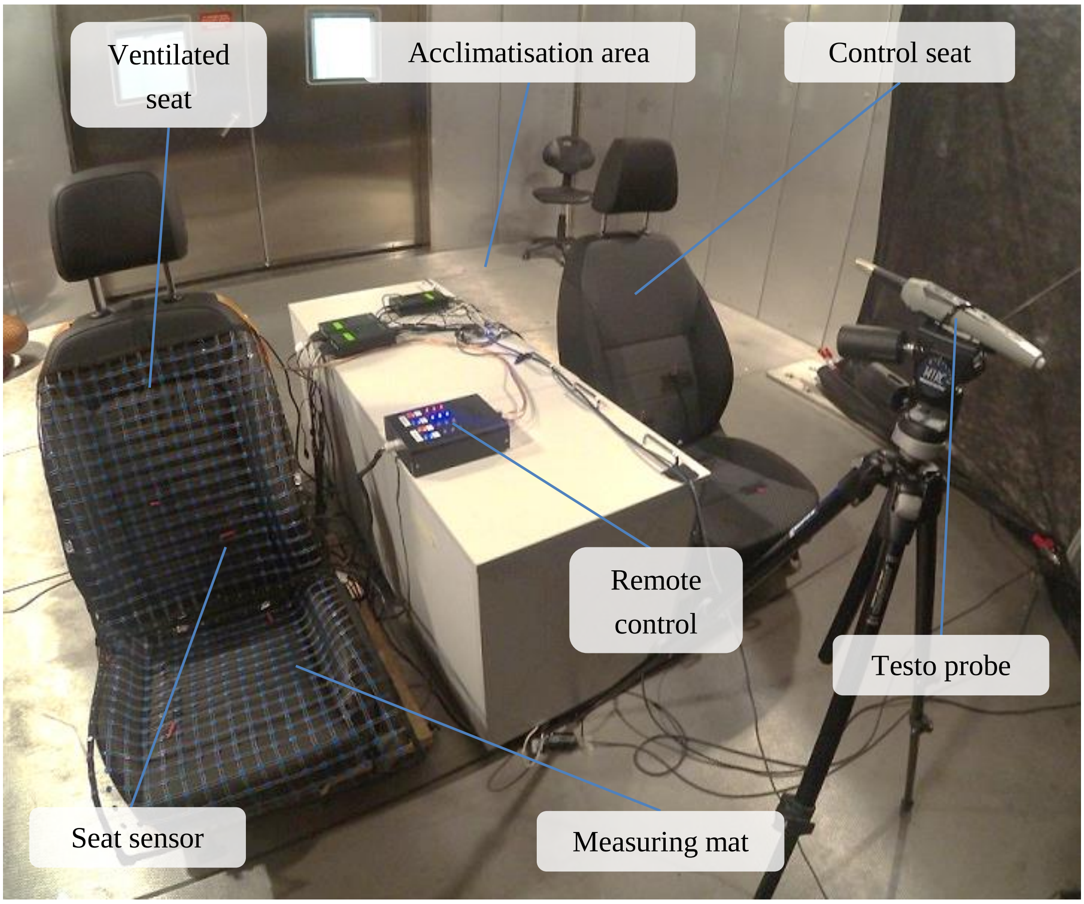


Figure 39) Measurement layout (front side view)

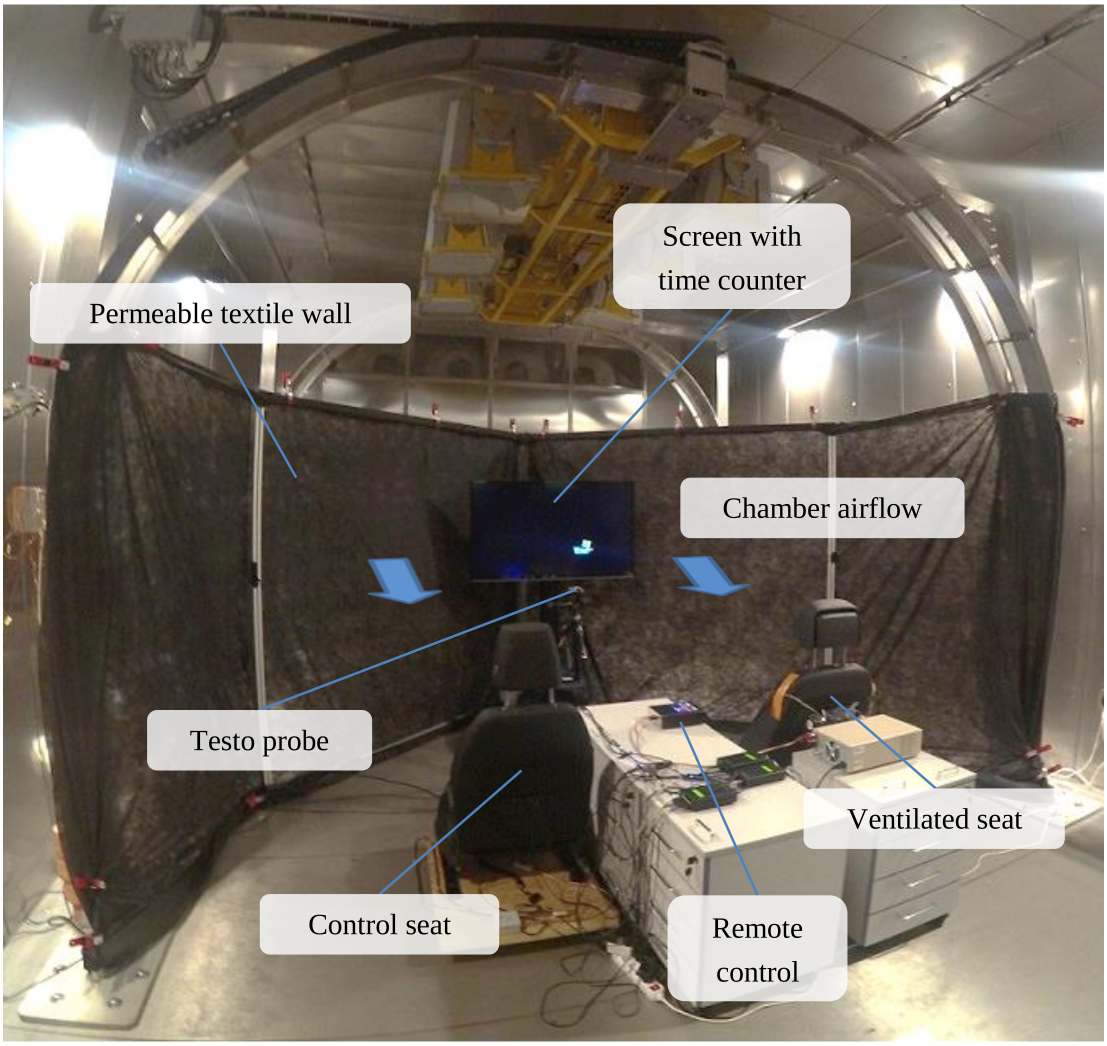


Figure 40) Measurement layout (back side view)

The permeable textile wall was used to reduce and homogenize the airflow made by the climate chamber. The average air speed was measured in the front of both seats in two points. First, the head area was 30 cm in the front of the headrest and 100 cm above the floor level. Second, the feet area was 60 cm in the front of the cushion front edge and 10 cm above the floor level. Measured values at the average ambient temperature of 22,2 °C and relative humidity of 22,2 % are shown in Table 5.

Table 5) Average air speed in the front of seats

	Control seat		Ventilated seat	
Position	Head	Feet	Head	Feet
Air speed [m/s]	0,32 ± 0,12	0,15 ± 0,04	0,20 ± 0,12	0,09 ± 0,08

4.4.2 MEASUREMENT PROCEDURE

For facilitation, the measurement procedure is represented by the process map, which is shown in Figure 41 and described below.

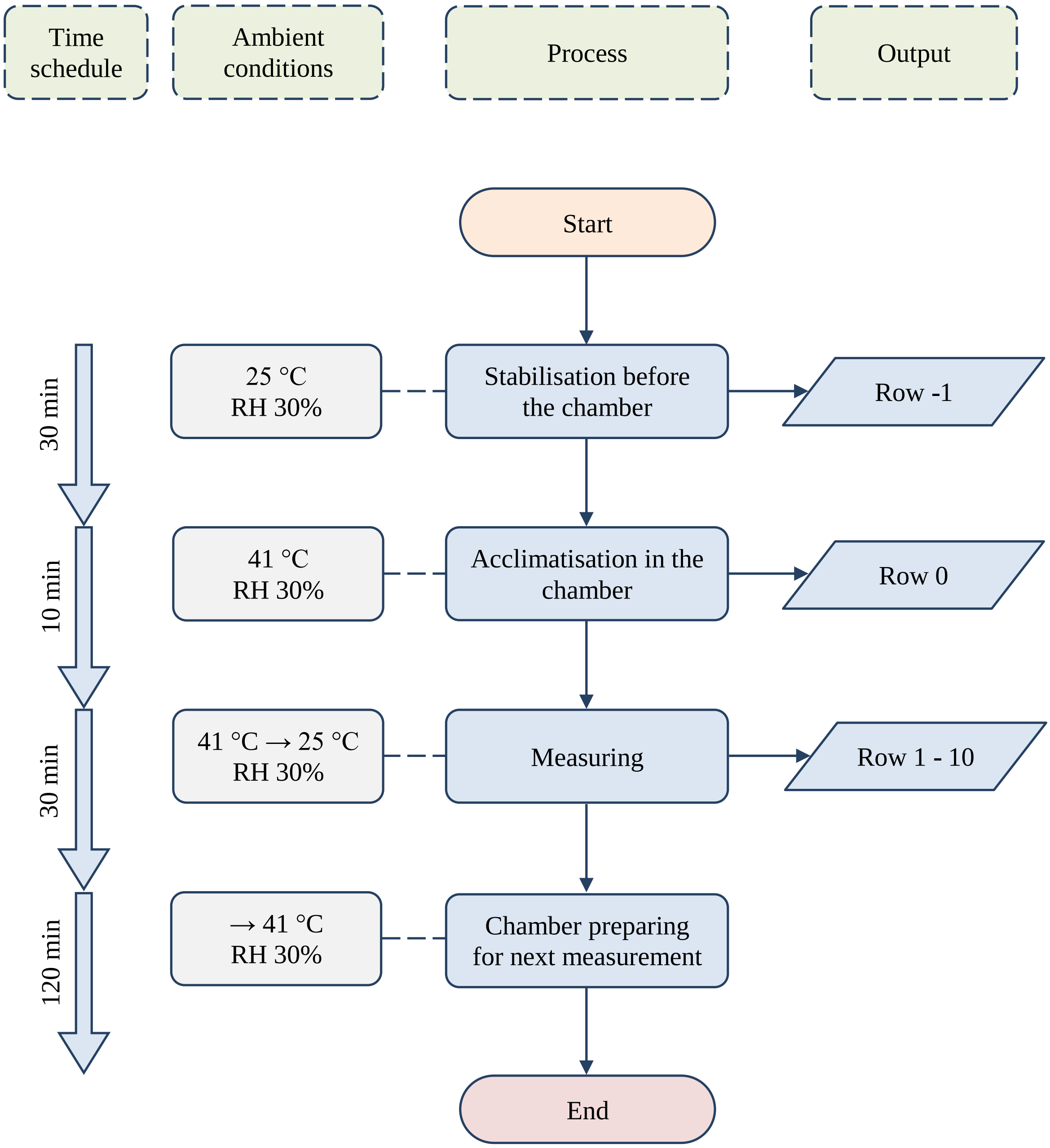


Figure 41) Measurement process map

Firstly, there was the stabilisation of the tested persons before they entered the climate chamber. It was situated in the room next to the chamber, where the ambient temperature was 25 °C, and relative humidity was 30 %. The stabilisation took at least 30 minutes. This first step should secure that persons were not affected by external climate conditions as well as different pre-test physical activities. At the end of the stabilisation, tested persons filled out the row -1 in the questionnaire.

Secondly, the tested persons entered the prepare climate chamber, where the temperature was set to 41 °C with 30 percent of relative humidity. This step took 10 minutes during which persons were doing light activity, walking around in the given area. This process should expedite the acclimatisation in the chamber to ambient conditions and simultaneously simulate the real situation when a person goes to the car from home or office during a hot summer day. At the end of the activity, tested persons filled out the row 0 in the questionnaire. It is also needed to be said, that during this two steps the blowers of the ventilated seat were running on the highest intensity of blowing or suction mode (depends on the test) to fully dry the seat and to achieve the same conditions as the surroundings.

After that, the tested persons took a seat. According to the schedule, one subject sat on the control seat and the other one on the ventilated seat. While they were seated, the clime chamber turned to the measuring mode. It means it turned from maintaining the temperature of constant 41 °C to cooling down up to final 25 °C, at sustaining 30 percent of relative humidity. The temperature drop with humidity can be seen in Figure 42. This measuring part took 30 minutes and should simulate the situation when the person has already got in the car and turn on the air conditioning to cool down the interior of the vehicle. During this time, respondents were filling out the rows 1 to 10 of the questionnaire every 3 minutes and could change the intensity of ventilation. The 3-minute interval was shown on the screen in front of them.

Finally, when the measuring procedure was done, and the tested persons went to relax to the 25 °C room, the climate chamber was turned to heating and maintaining mode of 41 °C and 30 percent of relative humidity and the blowers of the ventilated seat were set on the highest intensity of blowing or suction. This process took 120 minutes to secure the same starting conditions, both ambient and seats.

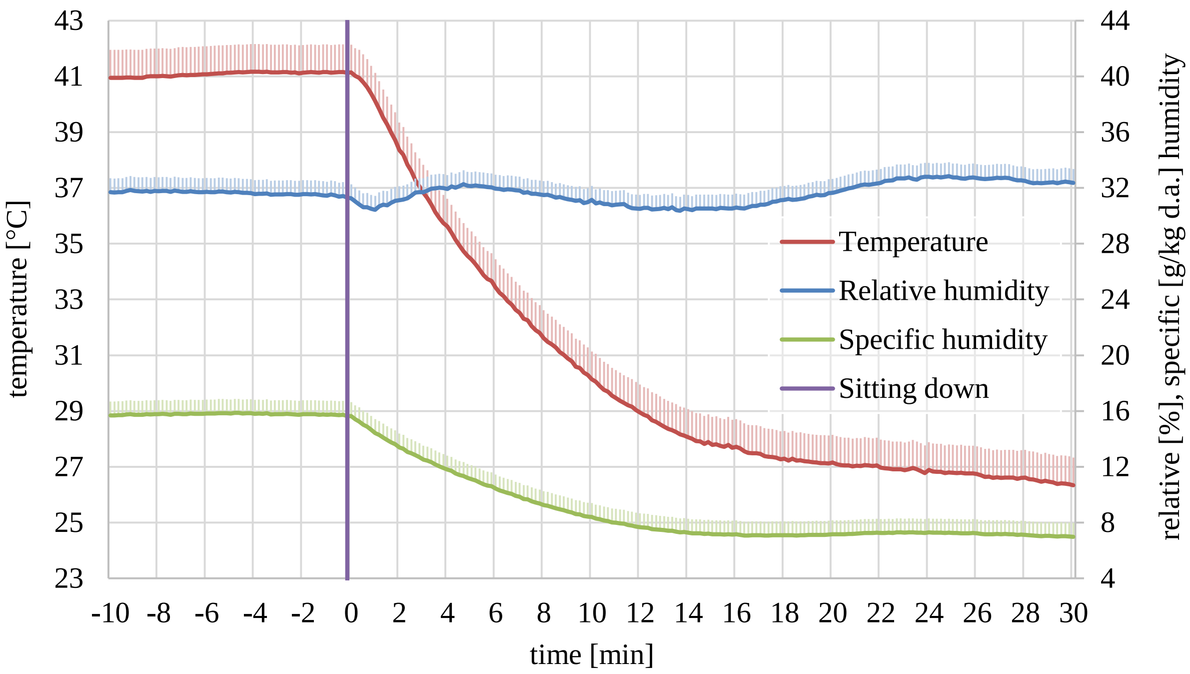


Figure 42) Ambient conditions during the measurement

From -10 to 0 minutes was the second step of acclimatisation in the climate chamber by the light activity. In 0 minute, tested persons took a seat and the climate chamber started with cooling for another 30 minutes. As it can be seen, firstly there was a relatively rapid fall which was reduced around the 14th minute and then went slightly to 25 °C.

4.4.3 QUESTIONNAIRE SURVEY

From previous measurements and experiences, it was set a universal questionnaire, shown in Figure 43, with appropriate scales, which allowed evaluating the thermal comfort of climate seats. His versatility also allowed comparing the achieved data with other methods, for instance, the measuring with the thermal manikin etc.

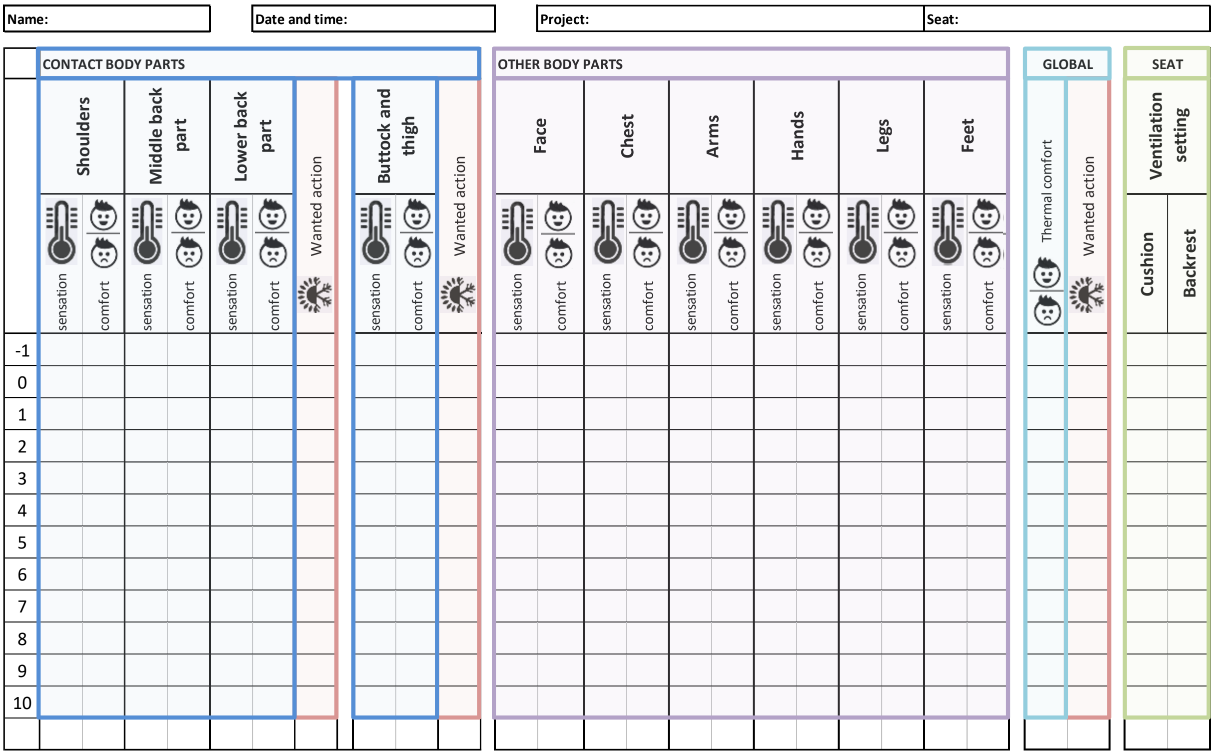


Figure 43) Questionnaire

The questionnaire was divided into individual parts of the human body (differ by methods), which were inspected from the point of view thermal sensation and comfort separately. Moreover, it was organized in four section, human body parts which were in contact with the seat, other body parts, overall assessment of thermal comfort and ventilation settings (in the case of the ventilated seat). Some of these sections were extended by the column called the wanted action, which supported to assess the thermal control from the different point of view. The appropriate scales of the thermal sensation, thermal comfort and wanted action are shown in Table 6. By ventilation setting, was meant the intensity, which could be adjusted in three steps or the ventilation could be completely switched off. This option was set to avoid potential health problems, which could occur. In this measurement, the data from the other body parts section were used for different purposes and used for different assessment method of thermal comfort. Therefore, that section is not evaluated in this work.

Table 6) Measurement scales

	Thermal sensation	Thermal comfort	Wanted action	
+3	Hot	Very comfortable	Intensively warm up	+3
+2	Warm	Comfortable	Warm up	+2
+1	Slightly warm	Just comfortable	Slightly warm up	+1
0	Neutral	-	No change	0
-1	Slightly cool	Just uncomfortable	Slightly cool down	-1
-2	Cool	Uncomfortable	Cool down	-2
-3	Cold	Very uncomfortable	Intensively cool down	-3

For the thermal sensation scale was used the ASHRAE scale. It can be said, that the thermal comfort scale was based on the MTV scale. However, it was subsequently significantly adjusted. It can be pointed, that there is no zero value, only +1 to +3 for comfortable feelings and -1 to -3 for uncomfortable feelings. Because the idea was that the person feels just comfortable or just uncomfortable and nothing between. Finally, the scale of wanted action was added to interpret, if the person desired to be warm up or cool down.

4.4.4 TESTED PERSON INFORMATION

Overall, this measurement participated nine persons of which were seven males and two females. Each person was tested on the control seat, without the ventilation function, and on the ventilated seat both in blowing and suction mode, in total every person did three measurements. The average physical values of the tested persons are shown in Table 7.

Table 7) Average physical values of the tested persons

Age [-]	28,1 ± 5,1
Weight [kg]	84,9 ± 7,0
Height [m]	1,8 ± 0,1
Body Mass Index (BMI) [-]	26,2 ± 2,6

4.5 EVALUATION

In this chapter, it was described the measurement methodology, which was used for the appraisal of the ventilated seat from the point of thermal comfort. Because thermal comfort is a subjective quantity, it will be used the mean value and the standard deviation for the further data processing.

The measurement was set in the climate chamber, which allowed to simulate hot summer conditions as well as to simulate the air conditioning turned on. For measuring ambient conditions such as temperature and humidity, it was used the Testo measuring device. For measuring the surface temperature and humidity on both seats, it was used four sensors per a seat, which were positioned to represent four areas - middle back, lower back, buttocks and thigh. The measuring mat used on the ventilated seat should support the overall temperature assessment by heat flux.

The tested objects were the control and primarily the ventilated seat. For the control seat, it was used a basic front seat from a volume car without any comfort function with covering from regular fabric. This seat was for the determination of default conditions. On the other hand, for the ventilated seat, it was used the special modification of the higher optional version of volume car, containing perforated leather, which allowed both mode blowing and suction. Moreover, it was set to deliver the same amount of air through the seat in both modes. The ventilation setting could be adjustable by the remote control, where besides was three-step intensity regulation, that the tested person could change. This option was mainly available to avoid potential health problems, which could occur. Moreover, in the front of the tested seats it was the permeable textile to stabilise the climate chamber airflow.

The measurement procedure was based on the long-term experience of the climate chamber and thermal comfort laboratories as well as it was adapted to their possibilities. The measurement process consisted of four steps. First, it was the stabilisation before the chamber at 25 °C for 30 minutes to get tested persons to the same default conditions. Second, it was the acclimatisation in the chamber at 41 °C for 10 minutes by the light activity walking around the given area. Third, it was the measuring part when the clime chamber turned to the cooling down mode, which took 30 minutes. In this part, the persons sat on the seats and filled out the questionnaire in the three-minute interval. At the end, when measuring was done, the climate chamber turned to the heating and maintaining mode of 41 °C. It took 120 minutes to be secured the same beginning conditions for another test.

This kind of the measurement procedure should simulate the real situation when a person goes to the car from home or office during a hot summer day, get in, turn on the air conditioning to cool down the interior of the vehicle, and drive for 30 minutes.

For the evaluation of thermal comfort, it was used the questionnaire survey divided into four section. However, data were assessed only from three of them, because the other body parts section was used for different assessment purposes. In total, it was used three scales, separately for the thermal sensation, thermal comfort and wanted action.

After all, the measurement participated nine persons. Each person was tested on the control seat, and on the ventilated seat both in blowing and suction mode.

5 EXPERIMENTAL MEASUREMENT – TEMPERATURE AND HUMIDITY

In this chapter, it will be shown all results concerning measured temperatures and humidity. They will be clearly depicted in various charts. In every chart, it will be shown values from all three measured seats for easy comparison. The control seat curves will be displayed by red colour, the blowing mode of the ventilated seat by blue colour, and the suction mode by green. Purple colour will be used for the zero line defining the sitting-down state on the tested seats.

Firstly, it will be shown temperature results, Figure 44 to Figure 47, separately from backrest and cushion part. Furthermore, they will be divided into individual areas. The backrest to middle back and lower back area and the cushion to buttocks and thigh. Then, it will be the summary, where it will be compared values for the backrest and the cushion as wholes, Figure 52 and Figure 53.

Secondly, it will be shown humidity results, Figure 48 to Figure 51, in the same order as temperatures. Also with the summary for the backrest and the cushion as wholes, Figure 54 and Figure 55. Humidity will be represented by specific humidity.

Moreover, the results will be supported by the heat flux measuring separately for the backrest and the cushion, Figure 56 and Figure 57.

After each part, it will be done an overall evaluation of all depicted results.

5.1 Temperature

5.1.1 Backrest

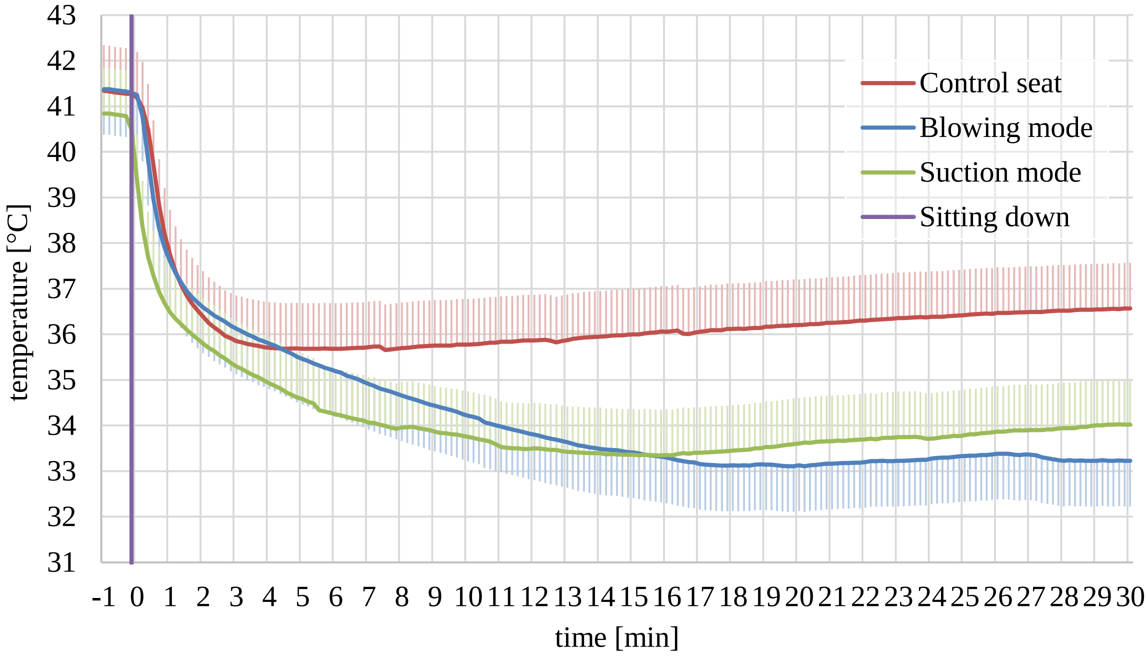


Figure 44) Middle back area – temperature

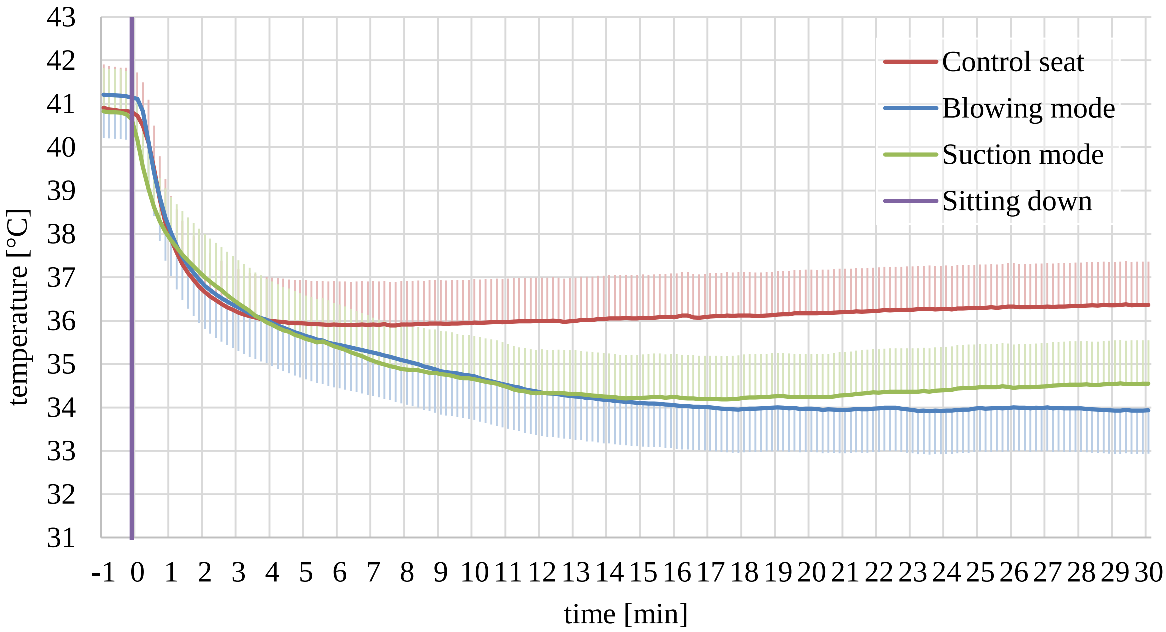


Figure 45) Lower back area – temperature

5.1.2 CUSHION

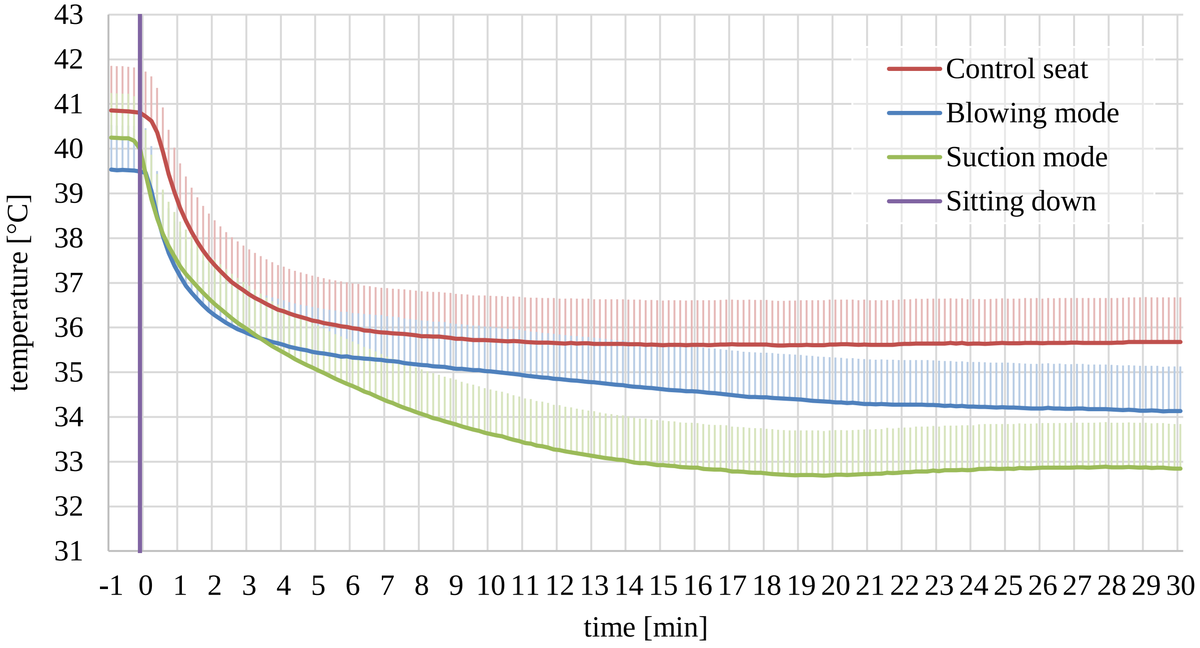


Figure 46) Buttocks – temperature

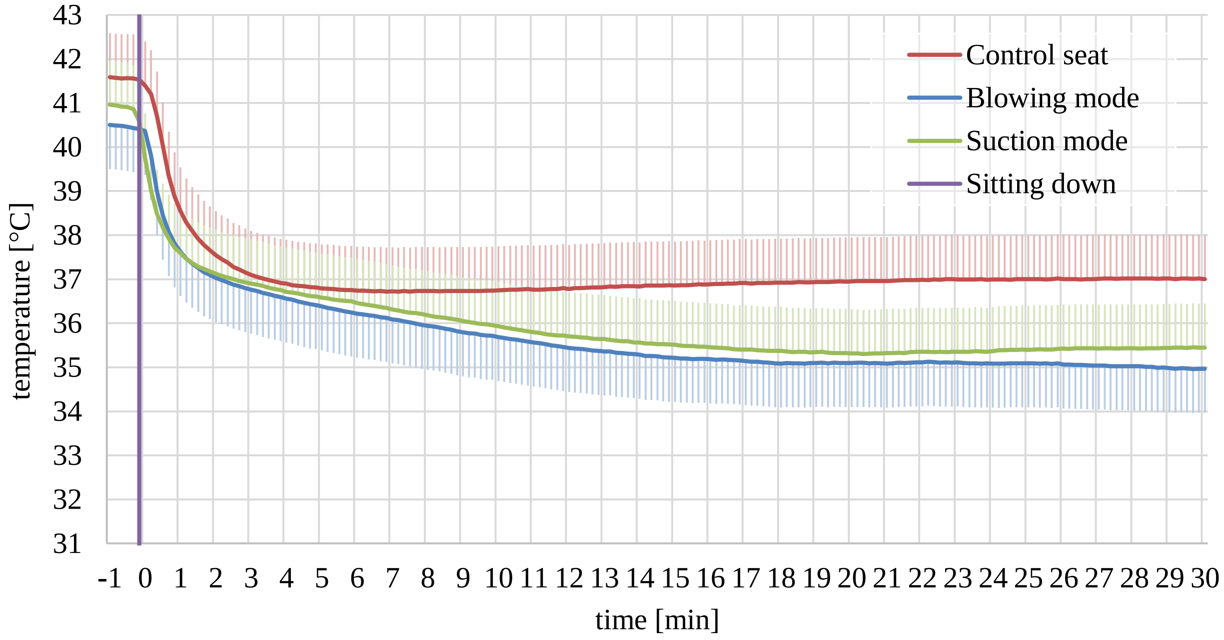


Figure 47) Thigh – temperature

5.1.3 SUMMARY

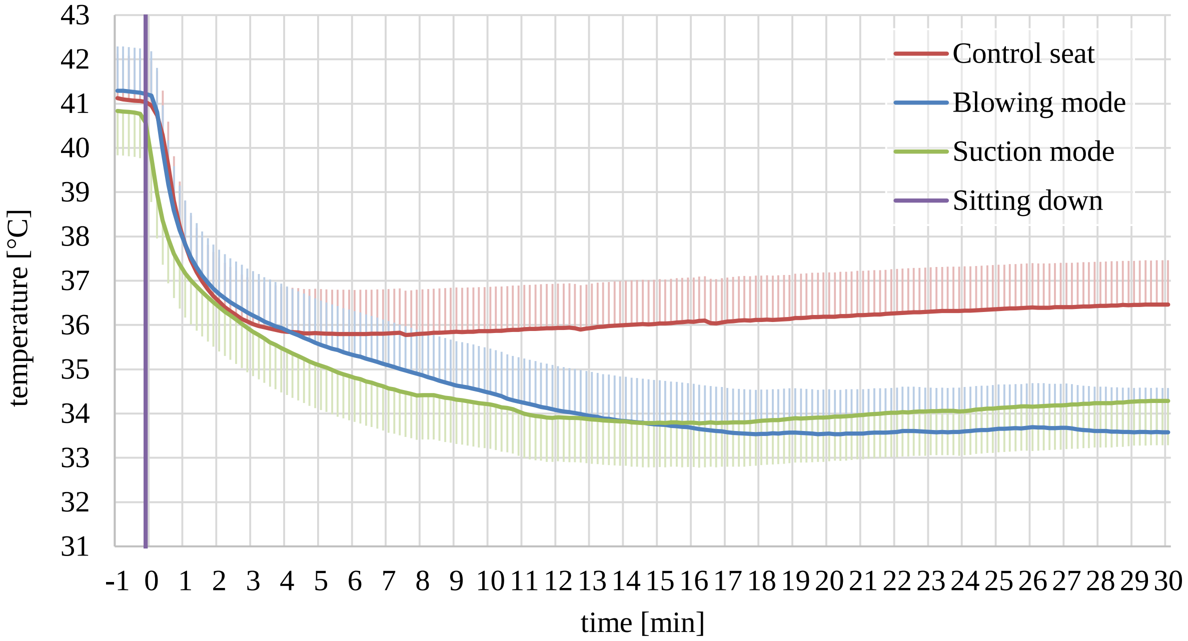


Figure 48) Backrest – temperature

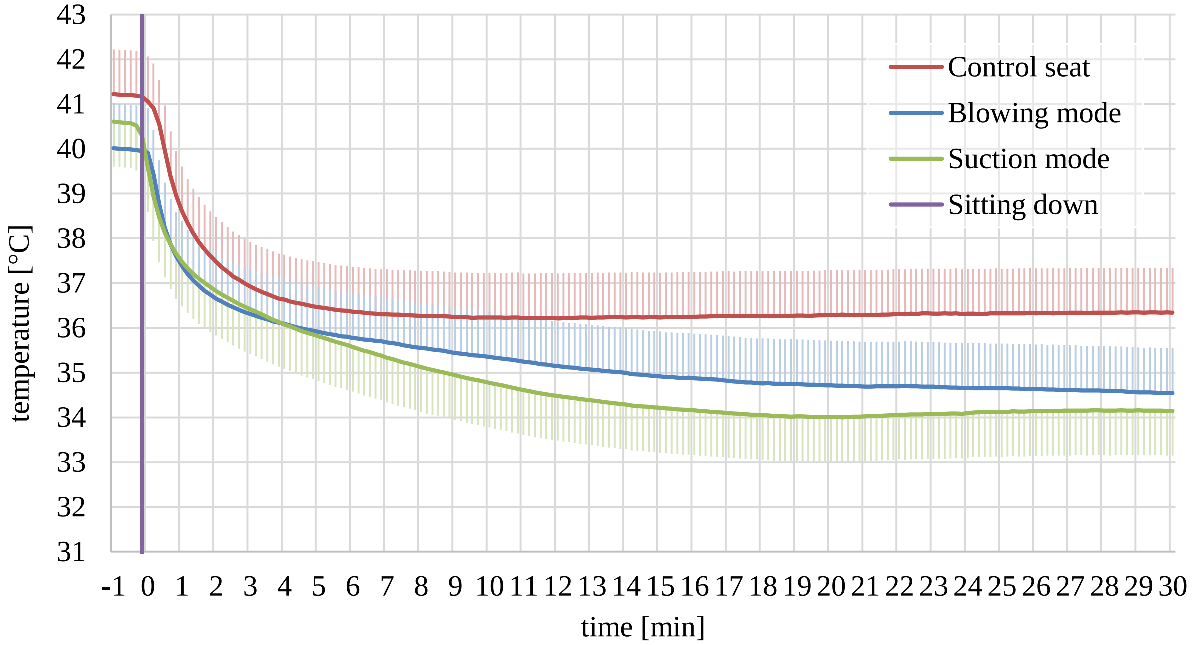


Figure 49) Cushion – temperature

5.1.4 EVALUATION

The backrest was divided into two areas. In the middle back area, Figure 44, it can be seen, that the mean value of the suction mode is more efficient than the blowing mode up to 15 minutes, then the suction mode goes slightly to higher temperatures than the blowing mode. It could be done, because in the beginning, the blowing mode blows the ambient air, which is quite warm. However, after that, it can provide better and stable results than the suction mode.

In the lower back area, Figure 45, it can be seen, that first 15 minutes are quite same for both modes. After that, it can be seen the same trend as it was in the middle back area, which means while the blowing mode is steadily on 33,9 ± 1,3 °C, the suction mode goes higher to 34,5 ± 1,3 °C.

The difference between the middle back and the lower back area can be because of the blower position, which is in the upper part of the backrest, so there is stronger air flow.

The cushion was also inspected from two areas. In the buttocks area, Figure 46, it can be seen, that after three and half minutes there is a significant difference between these two modes. In contrast with the backrest, there is significantly more efficient the suction mode. The biggest difference is in 16 minutes. Then the suction mode goes slightly higher. However, it can be done by the ventilation intensity settings. Despite that, the final temperatures reach 32,9 ± 1,5 °C in the suction mode and 34,1 ± 1,2 °C in the blowing mode.

In the thigh area, Figure 47, it can be seen, that both modes are mostly the same, only the blowing mode is located after three minutes around the haft of a degree in lower temperatures. The blowing mode finishes at 35 ±0,8 °C and the suction mode at 35,5 ± 0,8 °C.

The significant difference in the buttocks area can be done because of the big pressure from the human body, so the blowing mode becomes inefficient. Moreover, it is difficult to distribute the fresh are in this mode equally. However, if the pressure is smaller, it becomes slightly more efficient the blowing mode, as it can be in the thigh area.

The overall backrest assessment is shown in Figure 52. It is the mean value of middle and lower back area. It can be seen, that both modes are obviously better than the control seat which finishes at 36,5 °C. Nevertheless, it has to be said, that the beginning, means up to three minutes all three tested situations have the same progress. As it was said, the suction mode seems to be better up to 15 minutes, after that the lower temperatures can provide the blowing mode with the final temperature of 33,6 ± 1,2 °C. The suction mode ends at 34,3 ± 1,3 °C.

On the other hand, in the overall cushion assessment, Figure 53, is better the suction mode which can provide from 4 minutes lower temperatures than blowing mode. In total, the control seat ends at 36,3 ± 0,8 °C, the blowing mode at 34,6 ± 1,1 °C and the suction mode at 34,2 ± 1,8 °C.

5.2 Humidity

5.2.1 Backrest

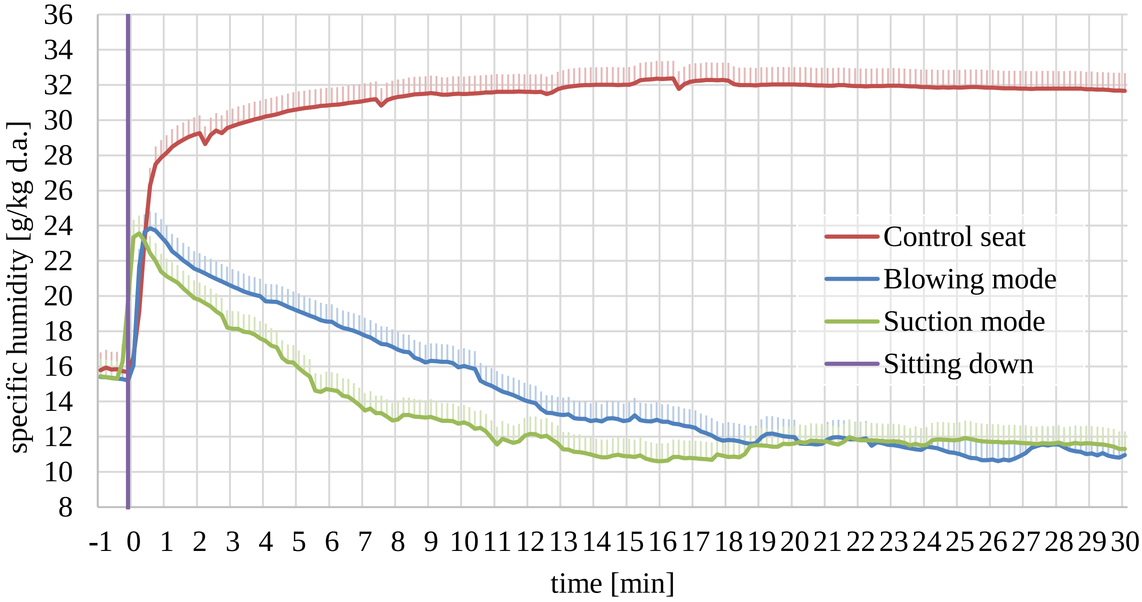


Figure 50) Middle back area – humidity

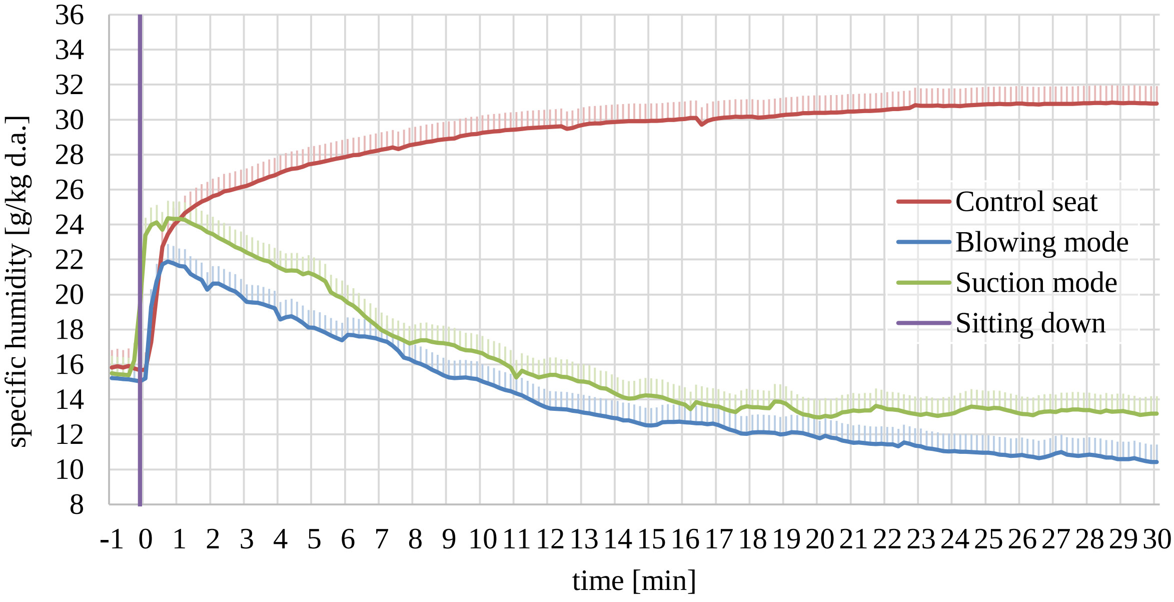


Figure 51) Lower back area – humidity

5.2.2 Cushion

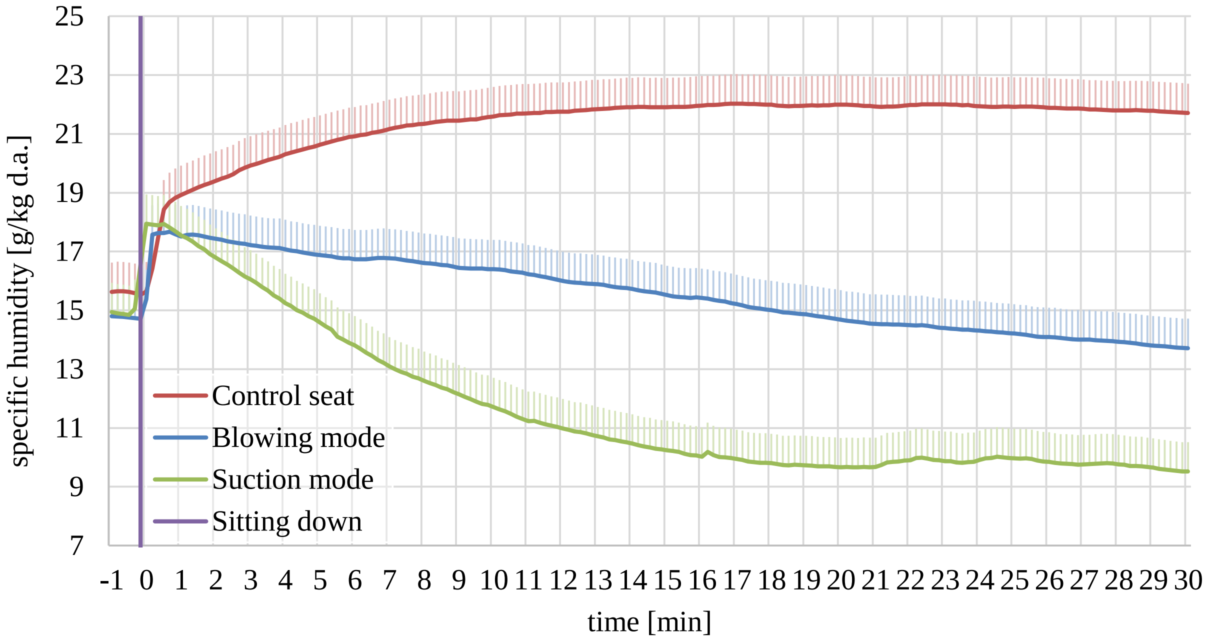


Figure 52) Buttocks – humidity

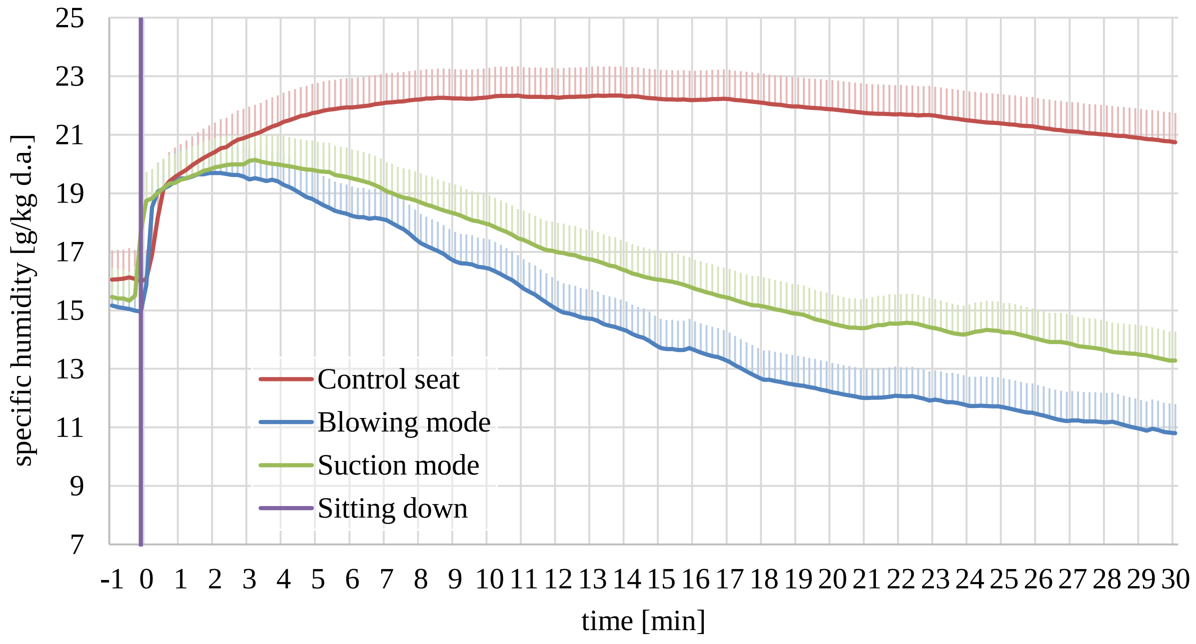


Figure 53) Thigh – humidity

5.2.3 SUMMARY

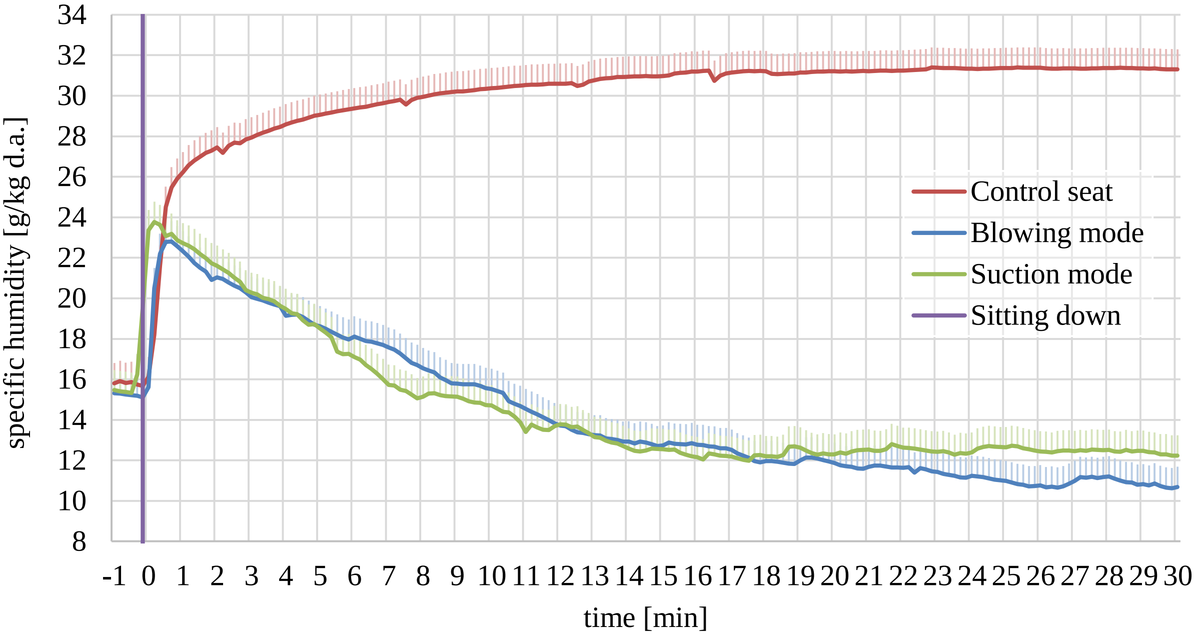


Figure 54) Backrest - humidity

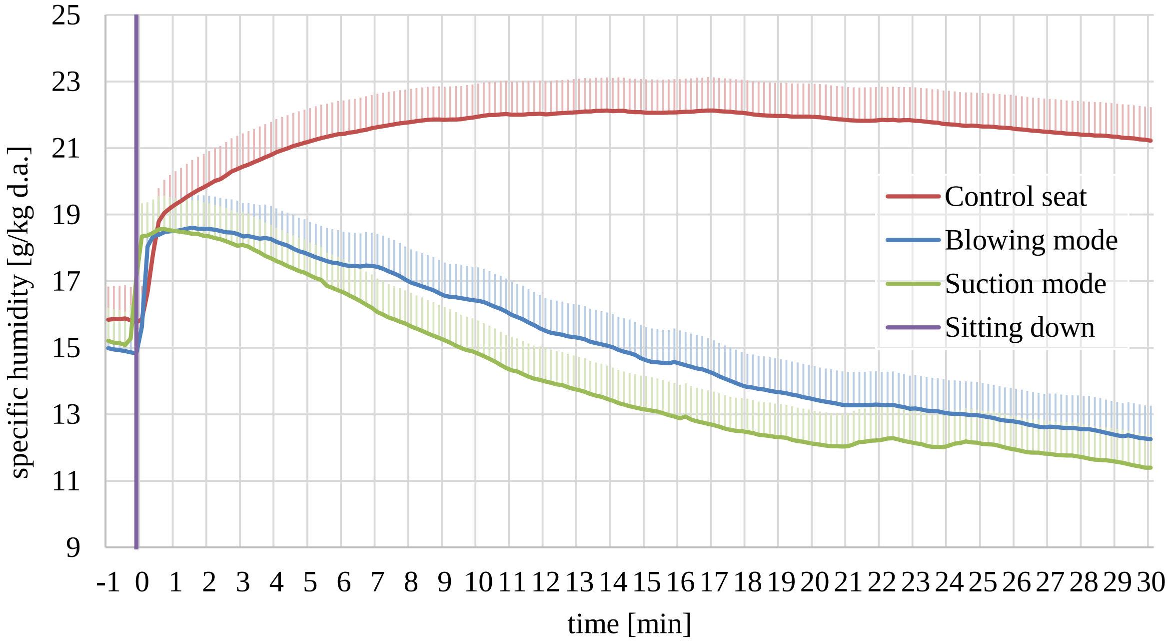


Figure 55) Cushion – humidity

5.2.4 EVALUATION

In the middle back area, Figure 48, it can be seen, that suction mode is more efficient than the blowing mode. Especially, eight minutes when there is the biggest difference. However, after 20 minutes both modes are quite same and finish in the suction mode at 11,3 ± 5 g/kg $_{d.a.}$ and in the blowing mode at 11 ± 2,8 g/kg $_{d.a.}$

In the lower back area, Figure 49, on the contrary, the lower values provide the blowing mode for the whole time of the measurement. It almost constantly lies around 2 g/kg $_{d.a.}$ below the suction mode curve. Finally, the blowing mode reaches 10,4 ± 2,7 g/kg $_{d.a.}$ and the suction mode 13,2 ± 5,3 g/kg $_{d.a.}$

Overall, it can be said, that both modes can provide approximately 20 g/kg $_{d.a.}$ lower values than the control seat.

In the buttocks area, Figure 50, it can be seen the significant difference between the blowing and suction mode. It can be said, that the suction mode is more efficient, the biggest difference of 5 g/kg $_{d.a.}$ is seen in 16 minutes. Then, it stabilises and finishes at 9,5 ± 3,5 g/kg $_{d.a.}$ On the other hand, the blowing mode ends at 13,7 ± 1,3 g/kg $_{d.a.}$

In the thigh area, Figure 51, there is similar progress as it was seen before in temperature. The blowing mode is almost constantly in lower values and finishes at 10,8 ± 1,8 g/kg $_{d.a.}$ The suction mode finishes at 13,3 ± 2,3 g/kg $_{d.a.}$

As it was said in the case of the temperature the difference in the buttocks area can be done because of the big pressure from the human body. The suction mode can better take the humidity outside from the surface of the temperature.

The overall backrest assessment is shown in Figure 54. Both modes have mostly the same progress. Nevertheless, the blowing mode has final value of 10,7 ± 2,7 g/kg $_{d.a.}$, which is lower than the suction mode which has 12,2 ± 5 g/kg $_{d.a.}$ This small difference can be done by ventilation settings of the intensity. On the contrast, the control seat has final 31,3 ± 5,1 g/kg $_{d.a.}$

On the contrary, in the overall cushion assessment, Figure 49, it can be seen the constant difference, when the suction mode provides lower temperatures for all time. Nevertheless, it should be said, that the fluent decrease of the suction mode is reduced in 21 minutes, which can be affected by the ventilation setting of the intensity. Finally, it ends at 11,4 ± 3,5 g/kg $_{d.a.}$ while the blowing mode at 12,3 ± 2,2 g/kg $_{d.a.}$

5.3 HEAT FLUX

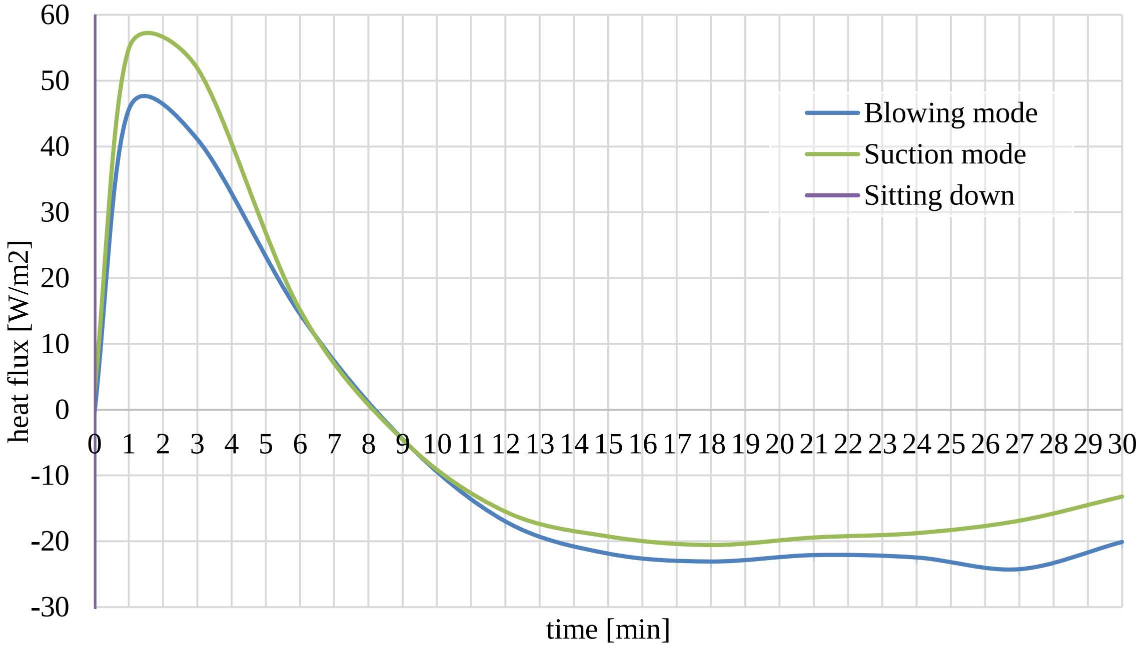


Figure 56) Backrest – heat flux

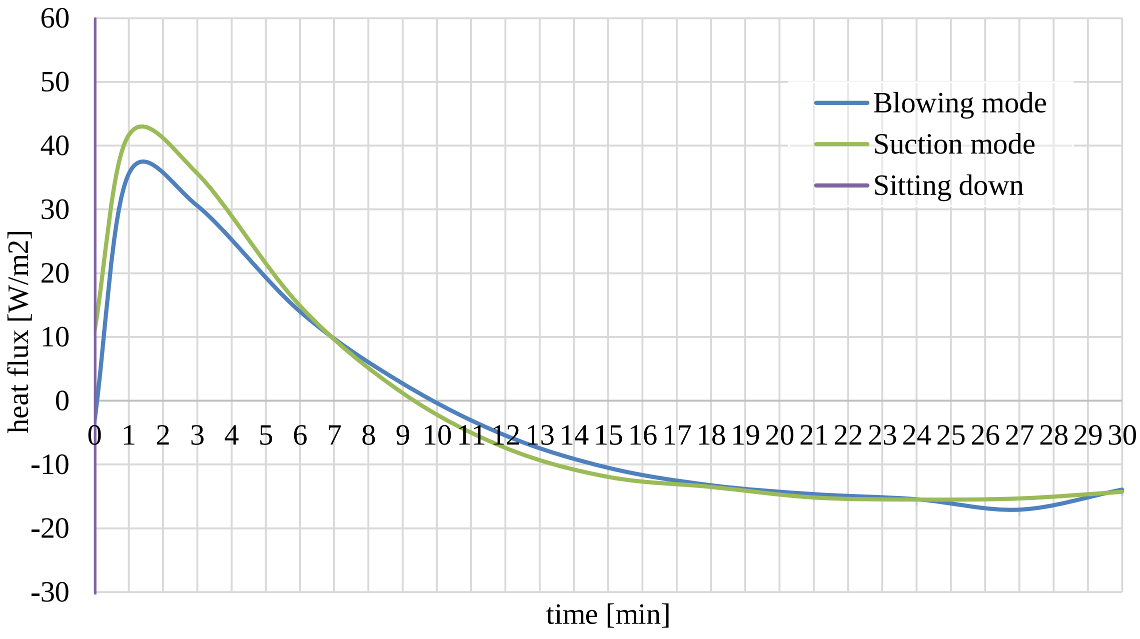


Figure 57) Cushion – heat flux

5.3.1 Evaluation

As the support quantity to temperature and humidity, it was also measured heat flux. For backrest, it is shown in Figure 56. It can be seen, that both modes have approximately same progress. Nevertheless, up to five minutes, there is higher heat flux for the suction mode, then until eleven minutes they have same values, and after that, the suction mode has slightly higher values again. The suction mode ends at -13,2 W/m^2 and the blowing mode at -20,1 W/m^2.

In the cushion, Figure 57, there is not seen some significant difference. Only in the beginning where the suction mode has again higher heat flux. Both modes finish around -14,1 W/m^2.

6 EXPERIMENTAL MEASUREMENT – THERMAL SENSATION AND COMFORT

The second part of the experimental measurement concerning thermal sensation and comfort will proceed similarly as the previous part Chapter 5.

Firstly, it will be shown thermal sensation results, Figure 58 to Figure 62. Secondly, it will be shown thermal comfort results, Figure 63 to Figure 68. Thirdly, results from the wanted action, Figure 69 to Figure 71. Finally, it will be shown results from ventilation settings of the intensity, Figure 72 and Figure 73. Additionally, it is reminded, that the individual scales are shown in Chapter 4.4.3 in Table 6.

Similarly, after each part, it will be done an overall evaluation of all depicted results.

6.1 THERMAL SENSATION

6.1.1 BACKREST

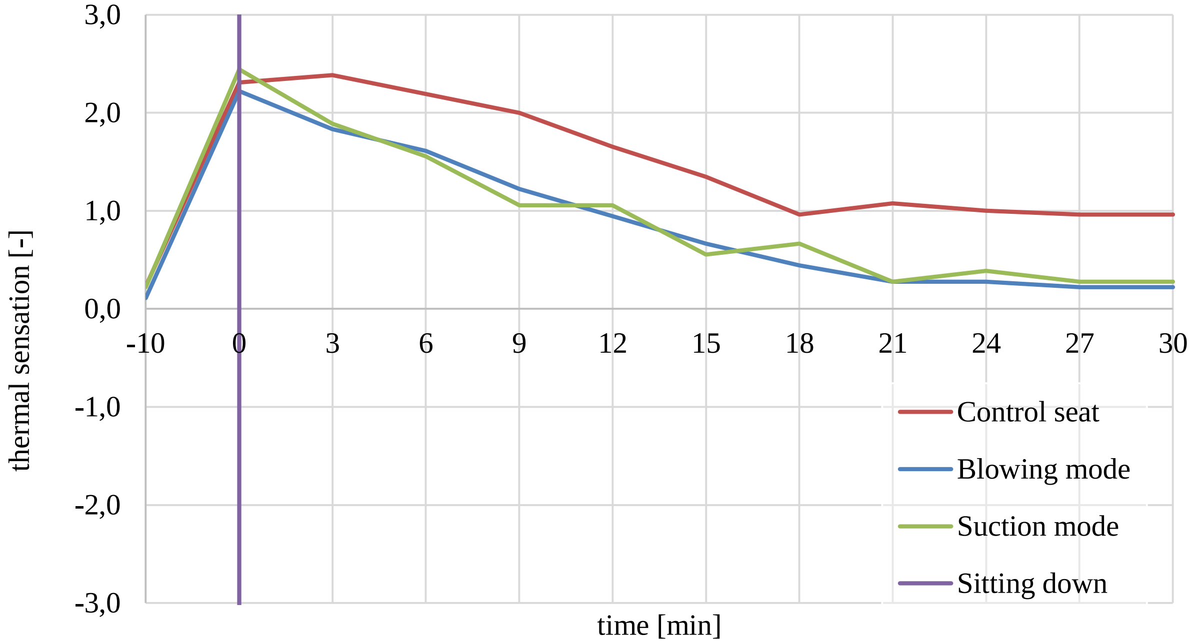


Figure 58) Shoulders – thermal sensation

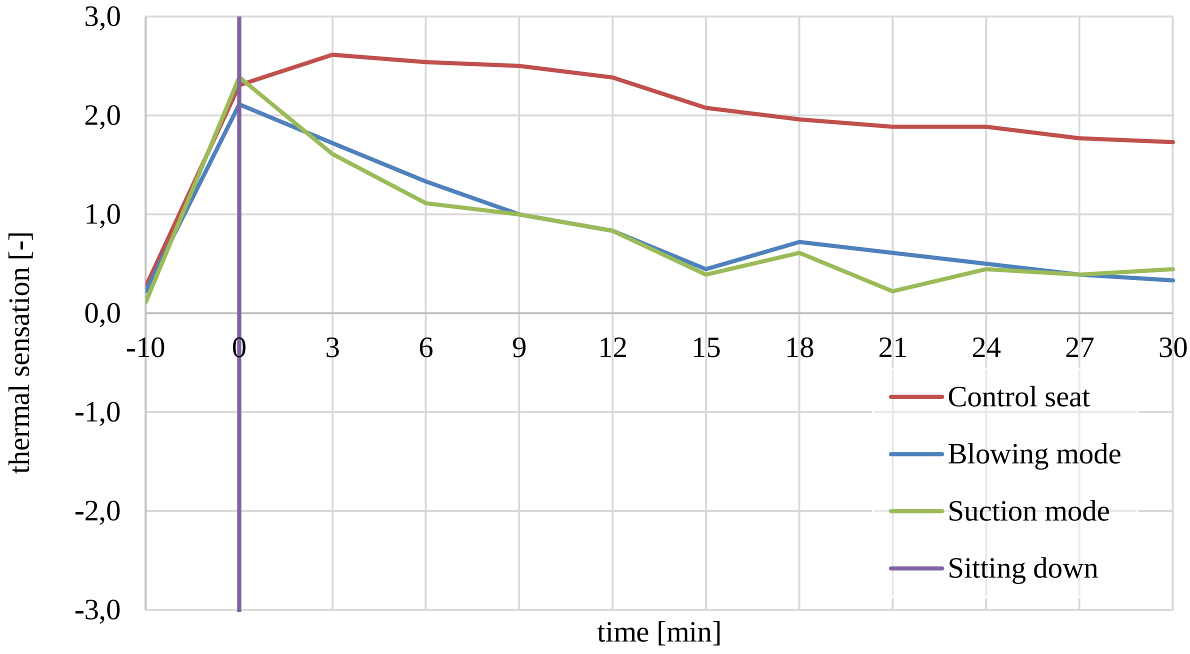


Figure 59) Middle back – thermal sensation

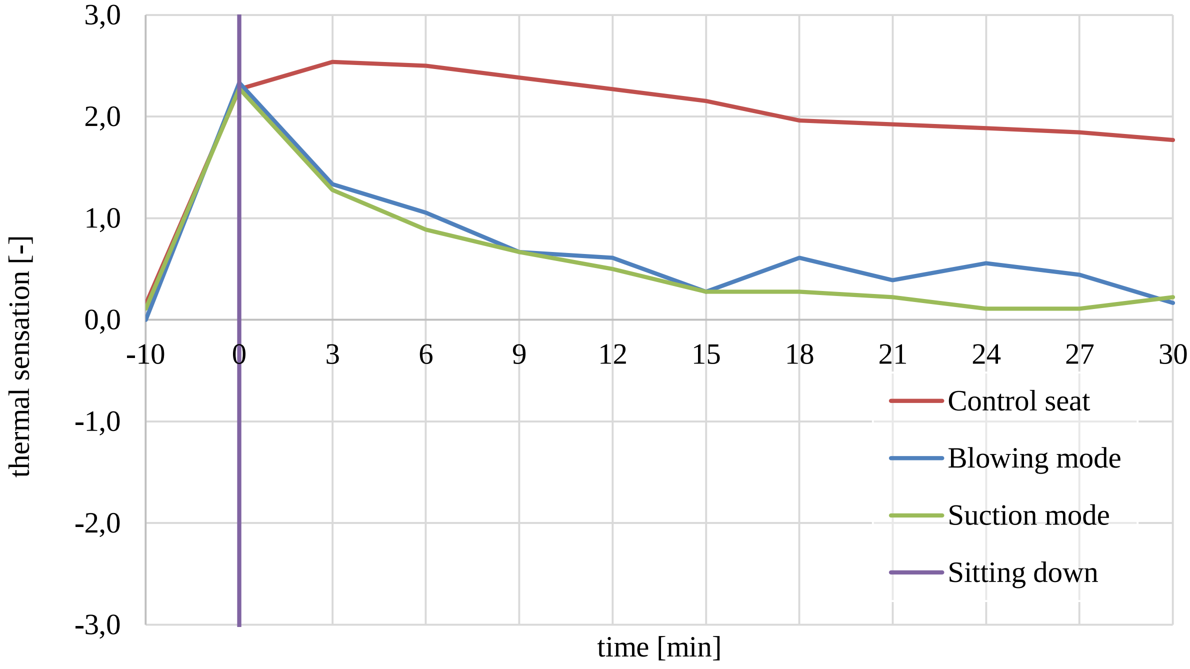


Figure 60) Lower back – thermal sensation

6.1.2 BACKREST SUMMARY

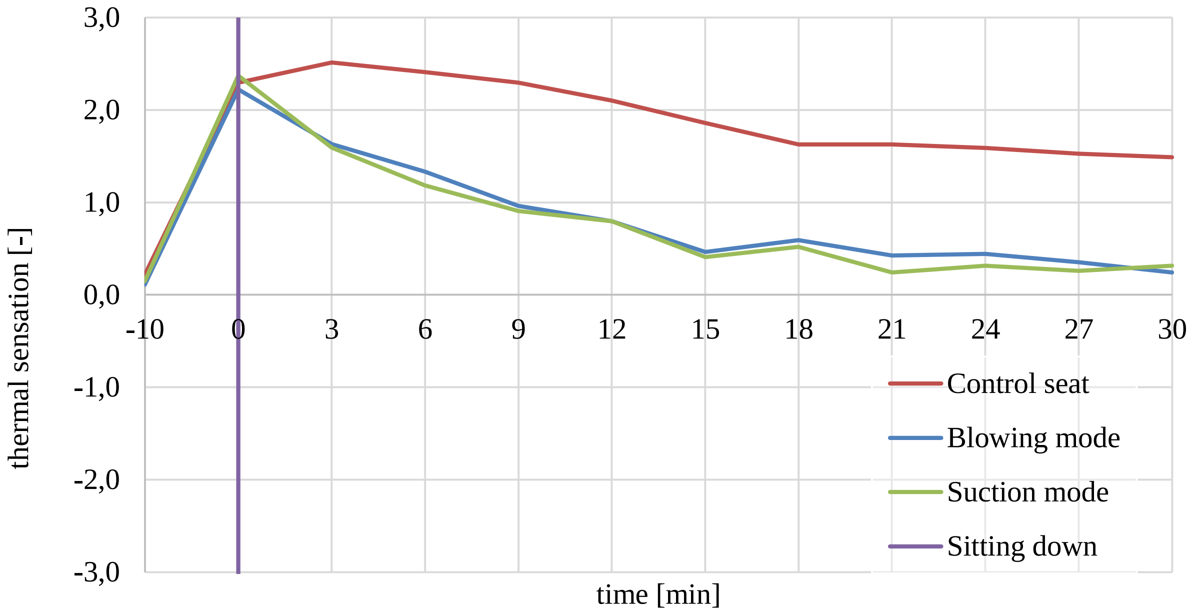


Figure 61) Backrest – thermal sensation

6.1.3 CUSHION

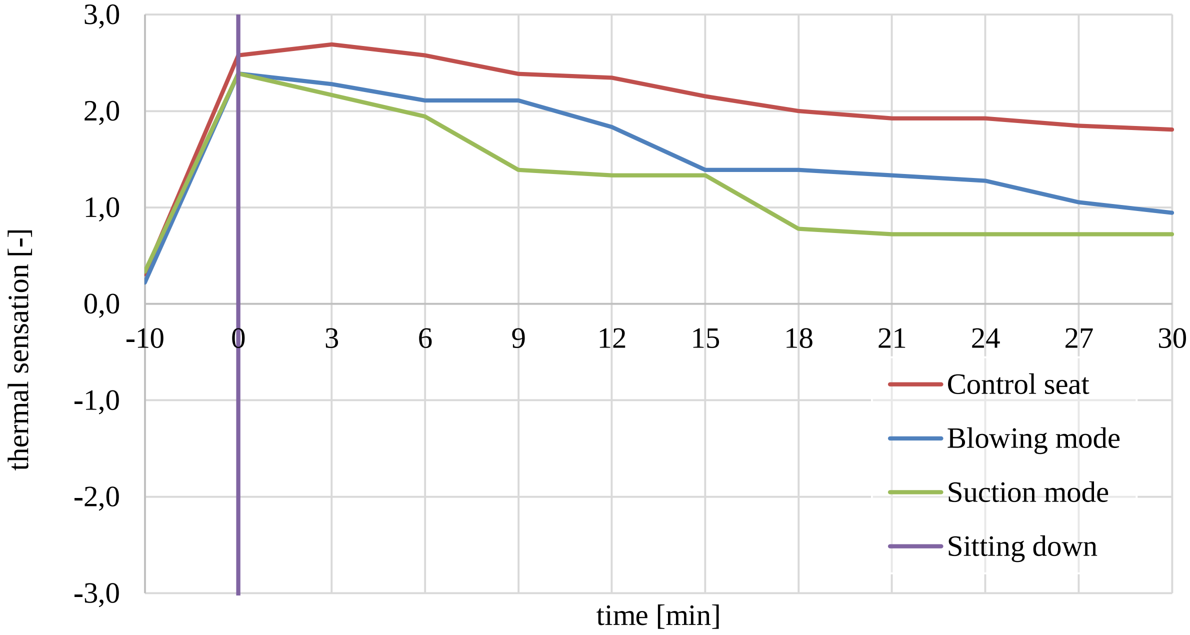


Figure 62) Cushion – thermal sensation

6.1.4 EVALUATION

In the shoulders area, Figure 58, there is no significant difference. Only it can be said, that the suction mode is more fluctuated than smoother blowing mode curve. Moreover, that all three measured combinations start at the same level, which is little above warm sensation. However, while the control seat finishes at the slightly warm level, the both ventilated modes end at little above neutral.

The middle back part, shown in Figure 59, has mostly the same progress as the shoulders part. Nevertheless, there is the steeper drop of ventilated seats. In six minutes, they are little above the slightly warm level. This can be affected by the location of the blower, which is situated in the middle back part and mostly provides the air from that area to downwards of the backrest. Anyway, the final values are the same for the ventilated seats. Nonetheless, for the control seat, the final value is little below the warm level.

The lower back area, shown in Figure 60, is mostly the same as previous middle back area. However, for the ventilated seats, it has the even steeper drop in the beginning. From 15 minutes, there is the fluctuation, which can be affected by ventilation settings. In total, the final values for all three seats are the same as in the previous middle back area.

Overall for the backrest area, Figure 61, it can be said, that both ventilated seats provide mostly the same thermal sensation. They can secure the almost neutral sensation against the control seat, which finishes in the middle between the slightly warm and warm level.

On the other hand, the results of cushion thermal sensation, shown in Figure 62, between ventilated seats have different signs of progress. In general, the suction mode curve is located in the lower values. Nonetheless, both modes end mostly at the same value of the slightly warm, the suction mode is a little bit lower. In total, also the control seat curve provides higher values and finishes almost at the warm level.

6.2 Thermal comfort

6.2.1 Backrest

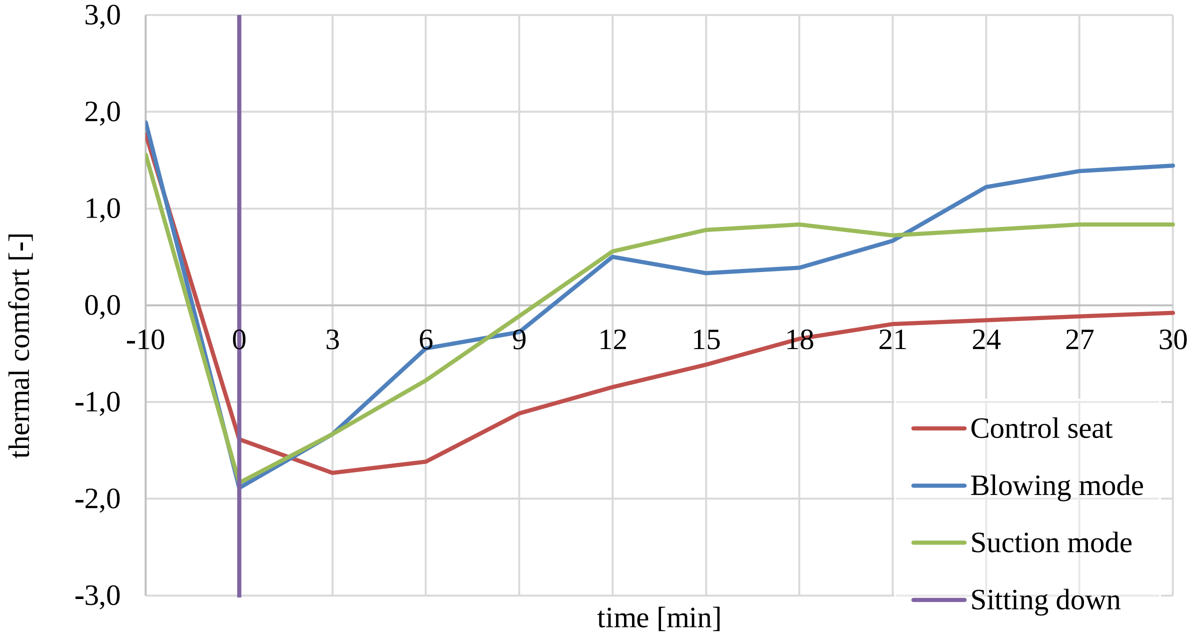


Figure 63) Shoulders – thermal comfort

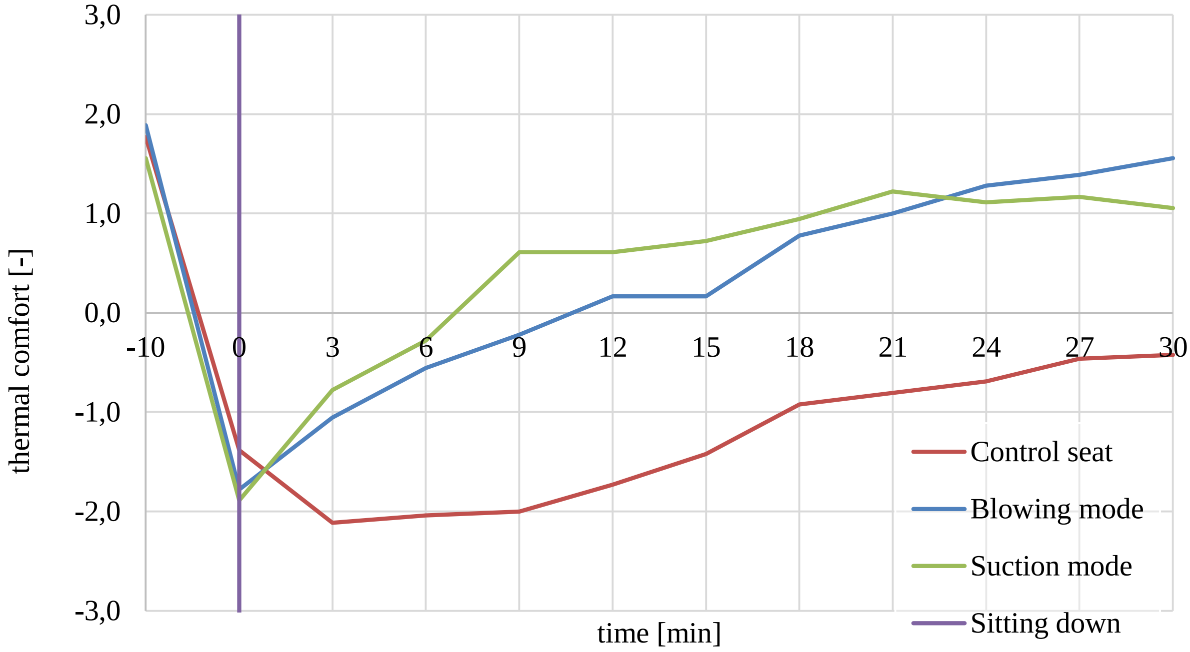


Figure 64) Middle back – thermal comfort

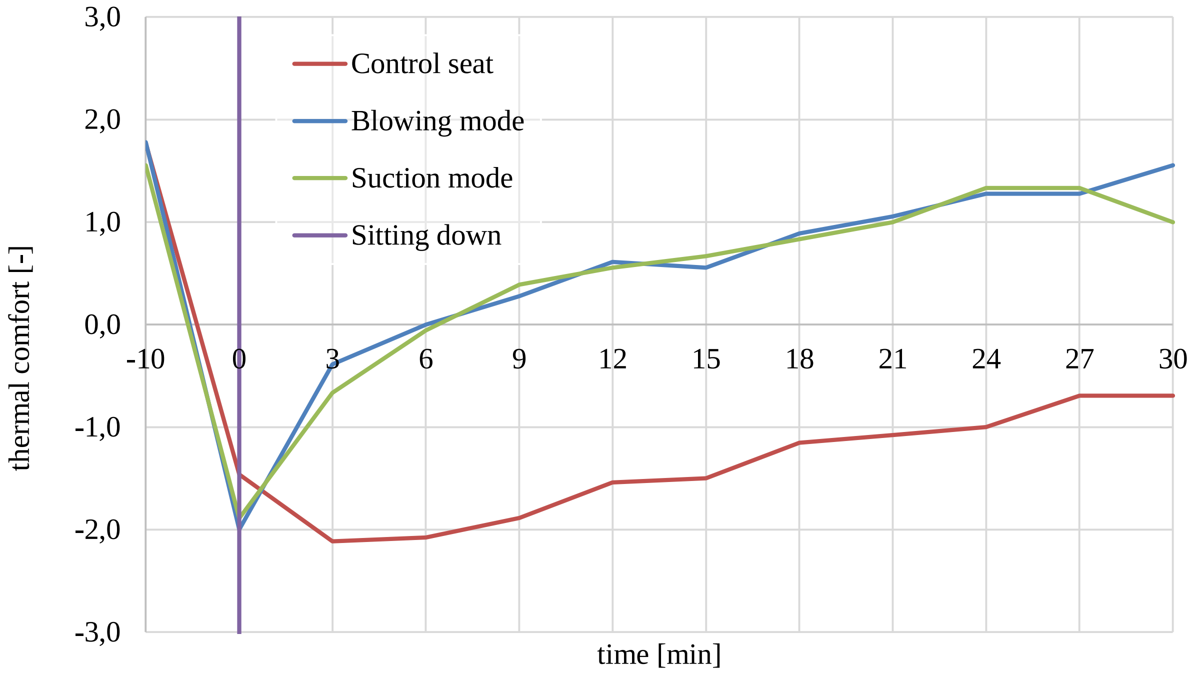


Figure 65) Lower back – thermal comfort

6.2.2 BACKREST SUMMARY

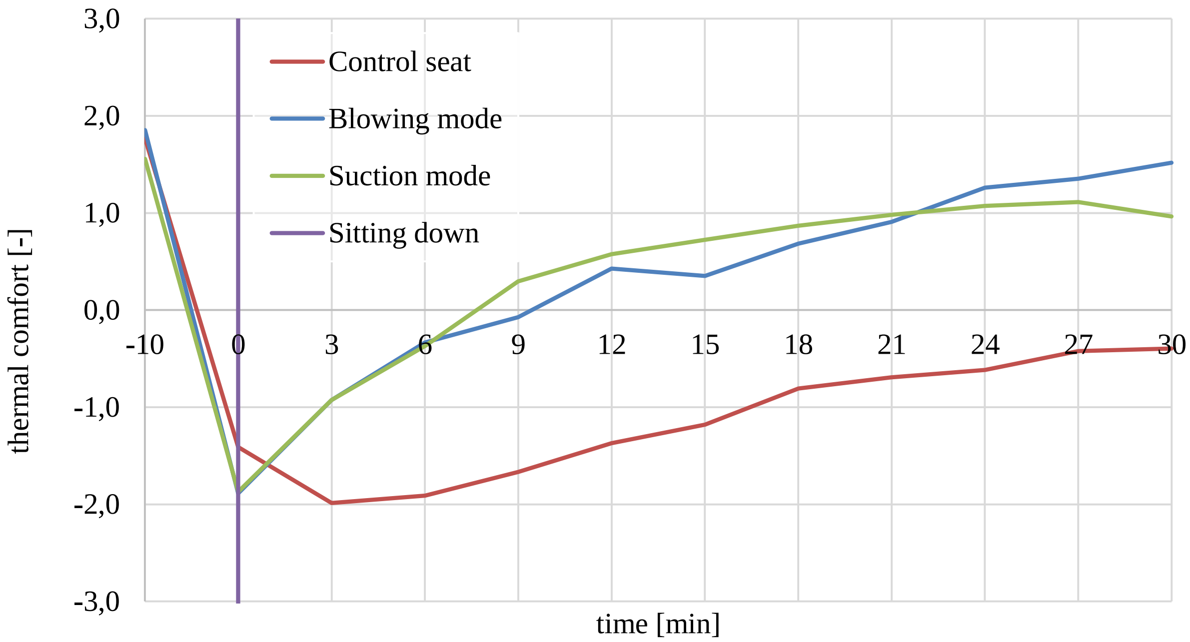


Figure 66) Backrest – thermal comfort

6.2.3 CUSHION

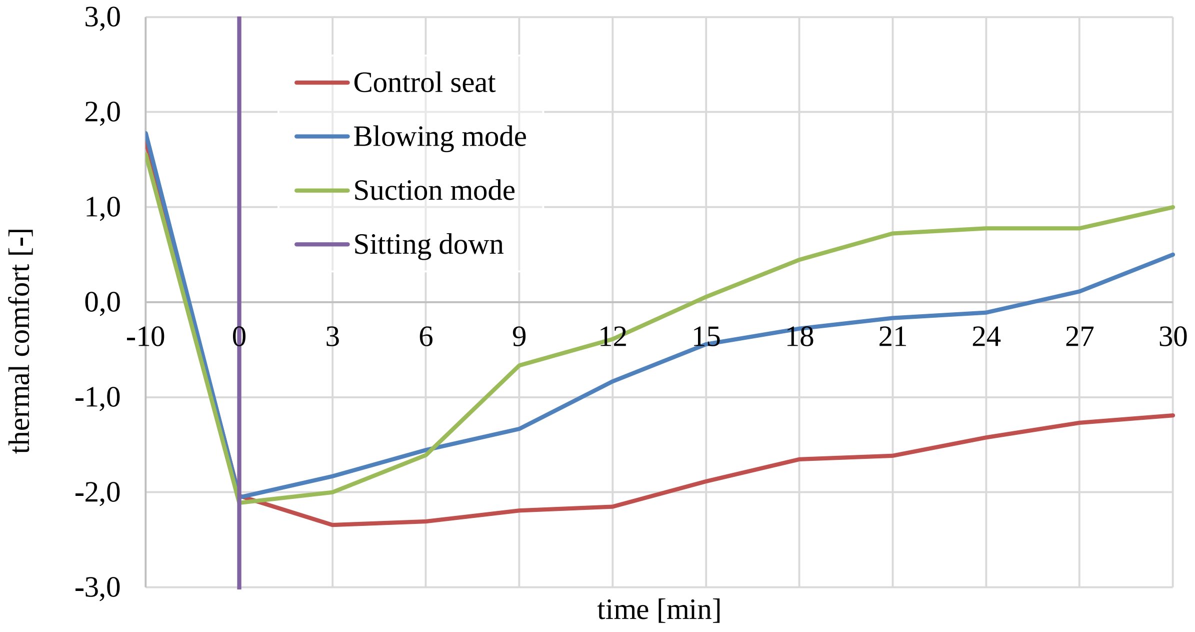


Figure 67) Cushion – thermal comfort

6.2.4 GLOBAL

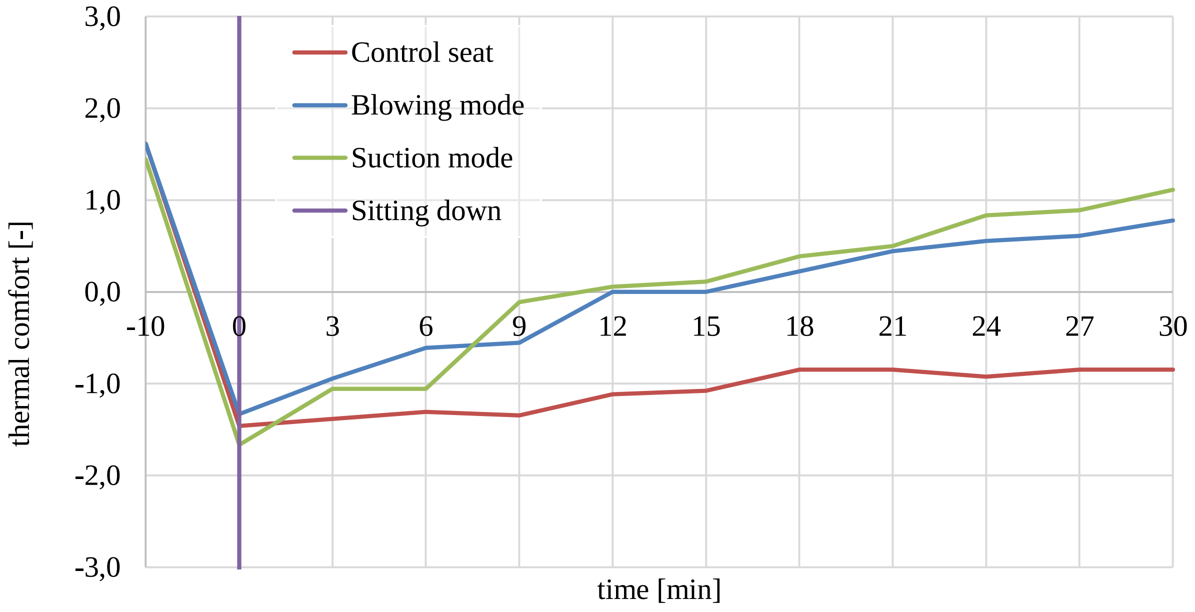


Figure 68) Thermal comfort – global

6.2.5 EVALUATION

In the shoulders area, Figure 63, in six minutes the blowing mode seems to be more comfortable. However, from 9 to 21 minutes the suction mode has higher values. Then, the blowing mode rises to the level between just comfortable and comfortable. The suction mode steadily goes to the little below just comfortable level.

In the middle back area, Figure 64, the suction mode is significantly in higher values up to 23 minutes. Then it steadily goes to the just comfortable level, while the blowing mode continues up to the same value as in the shoulders area. It can also be affected by the ventilation settings of the intensity.

In the lower back area, Figure 65, both modes have mostly the same progress. Only before the end in 27 minutes, they split and both ends as the previous situation.

The overall backrest summary in Figure 66 says that till six minutes both modes have the same effect on the thermal comfort. Then, they split, and the suction mode stays above the blowing mode up to 22 minutes, when they switch. The suction mode goes steadily to the just comfortable level, and blowing mode rises to the middle value between just comfortable and comfortable.

In the cushion area, Figure 67, after six minutes both modes significantly differ. Again, suction mode shows the higher comfort values. After 21 minutes it steadily goes to the just comfortable value, since the blowing mode reaches only the level under the just comfortable level.

The global thermal comfort in Figure 68 shows that the blowing mode is more effective in the beginning, exactly up to eight minutes, then the suction mode is more comfortable and ends at the just comfortable level. The blowing mode finishes slightly below the suction mode. So it can be said, that there is no significant difference.

6.3 WANTED ACTION

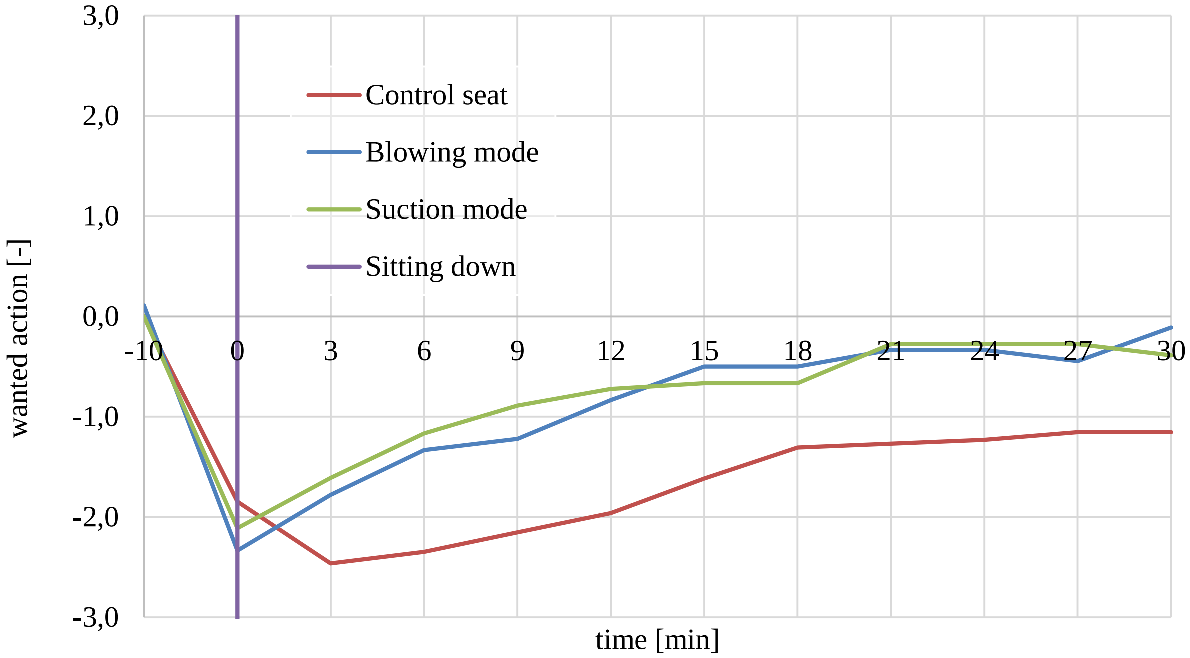


Figure 69) Backrest – wanted action

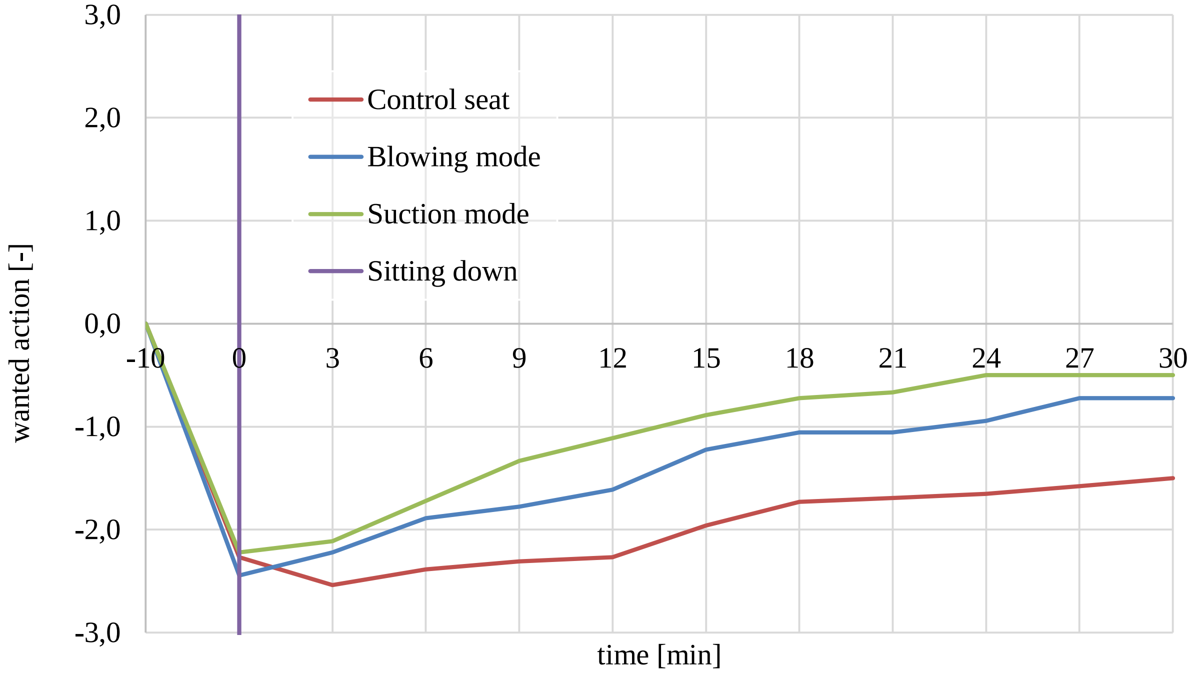


Figure 70) Cushion – wanted action

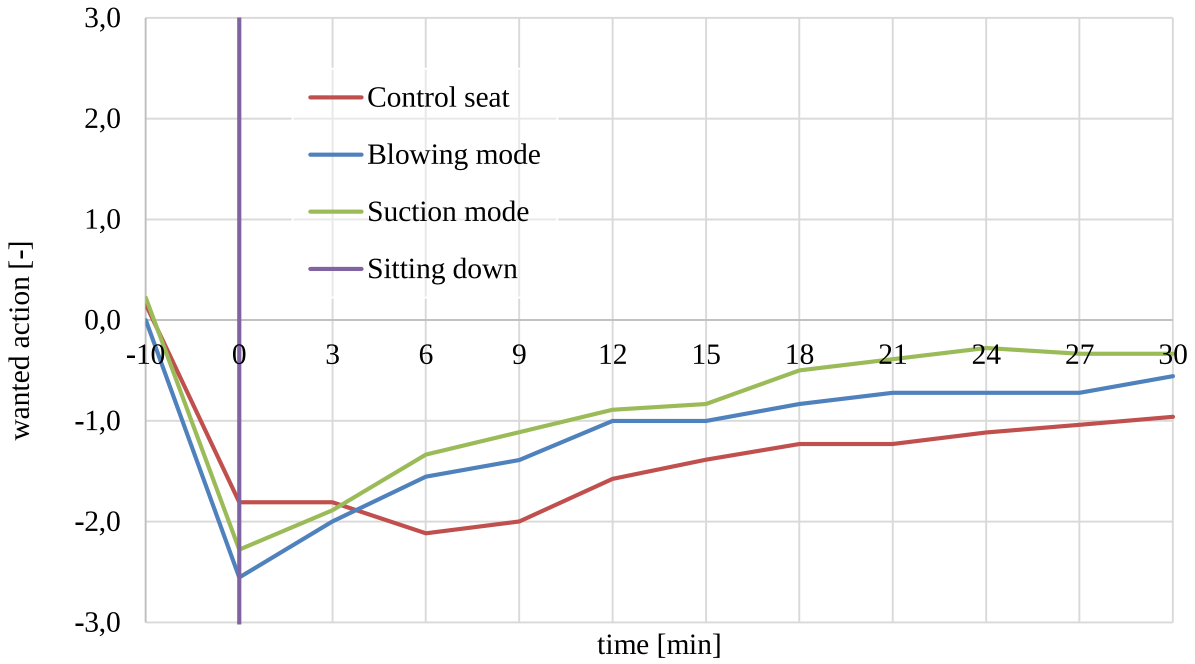


Figure 71) Wanted action – global

6.3.1 EVALUATION

In the backrest part, shown in Figure 69, the wanted action is in both modes mostly the same. However, the suction mode is located in the values closer to zero. In 13 minutes, both modes level off and finish slightly below the zero level, which represents no change desired. On the other hand, the control seat is situated under the level called cool down up to 12 minutes, when the ventilated seats are half below the zero level.

In the cushion part, Figure 70, it can be seen more significant difference between both modes. The suction mode values are closer to the zero level for the whole time. So it can be said, the suction mode is more effective concerning the wanted action.

The similar situation can be seen also in the global wanted action in Figure 71. By global, it was meant the whole body, not just the contact part with the seat. Therefore, it can be seen, that the control seat is not located in such lower values as it was in previous situations, because the ambient conditions also played a significant role.

6.4 VENTILATION SETTINGS

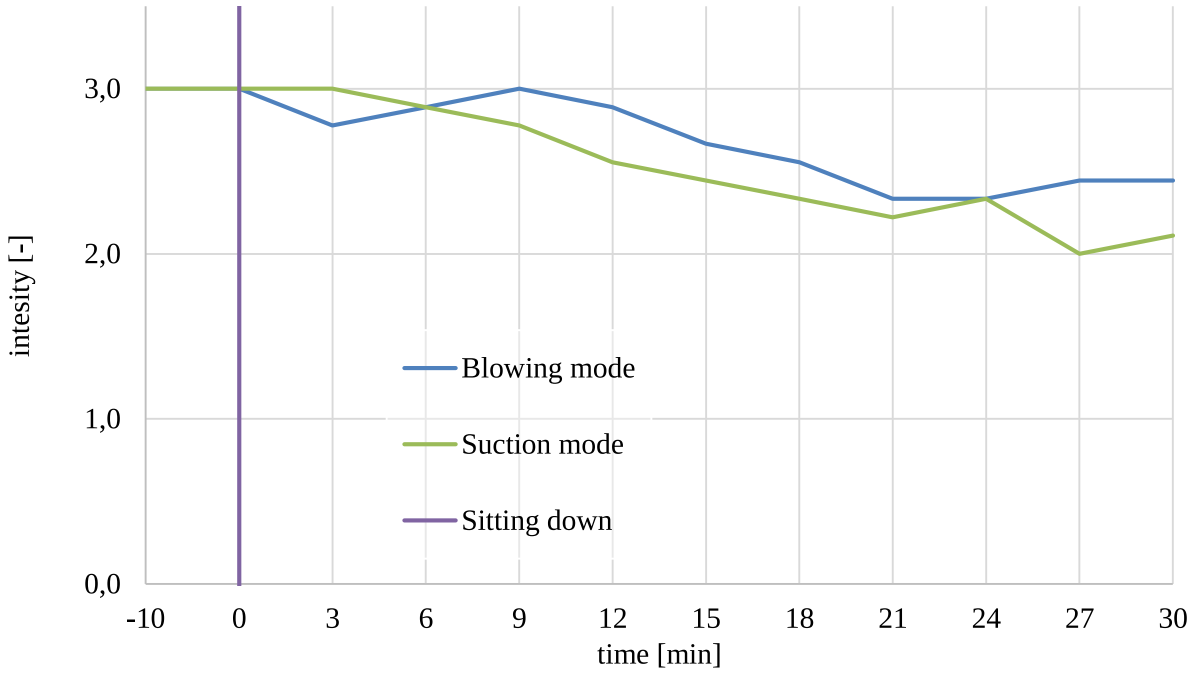


Figure 72) Backrest – ventilation settings

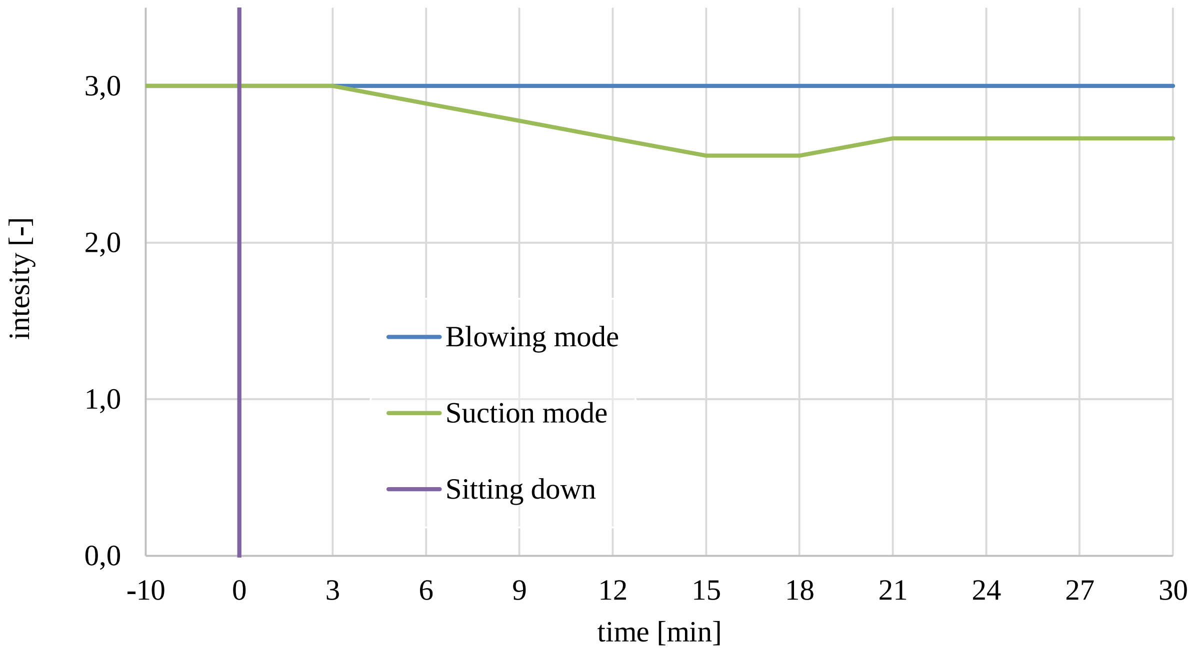


Figure 73) Cushion – ventilation settings

6.4.1 EVALUATION

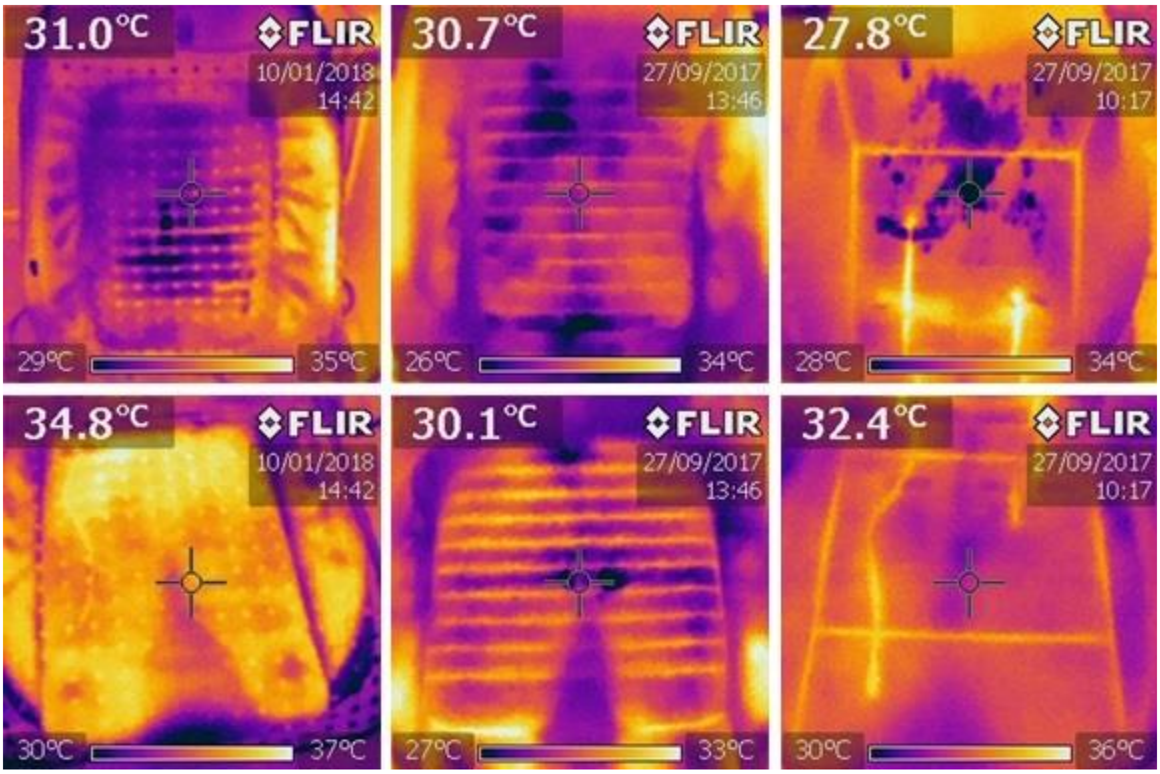
In the backrest part, shown in Figure 72, it can be seen, that there are changes in the ventilation settings of the intensity. The blowing mode is adjusted during the first three minutes. However, in nine minutes, it goes back to the maximum intensity. Then, it goes steadily down up to 21 minutes, when it levels off and stays at 2,4 of the intensity mean value. On the other hand, the suction mode is adjusted after three minutes and steadily goes down also up to 21 minutes. Then, it is readjusted and ends at the value 2,1 of the intensity mean value.

In the cushion part, shown in Figure 73, it can be clearly seen, that the intensity is not changed for the whole time in the blowing mode. On the contrary, the suction mode is adjusted after three minutes. It levels off between 15 and 21 minutes and then goes at the same value of 2,7 up to the end. Overall, it can be said, that the suction mode is more intensive and after while it should be adjusted to the lower intensity.

7 RESULTS ASSESSMENT

7.1 TEMPERATURE AND HUMIDITY

From the temperature evaluation it comes out, that for the middle back area the better solution is, in the beginning, the suction mode up to 14 minutes, then is better the blowing mode. Nevertheless, it is affected by the ventilation settings, which was set for the suction mode after five minutes at the lower intensity for the all backrest part. In the lower back area, the temperatures are mostly the same. Only the blowing mode seems to be located in the lower values. This progress is also supported by similar results from the evaluation of humidity. Therefore, from the point of temperature and humidity, it can be suggested three solutions. Considering two blowers in each area, for the middle back area using the suction mode and for the lower back area the blowing mode. Considering one blower, but with the adjustable air direction, which in the beginning runs with suction mode and then after 14 minutes changes to the blowing mode. Finally, considering only one blower, it can be suggested the suction mode. For example, in Figure 74, there are shown the thermal camera pictures of all three measured seats after the measurement. There is always separated picture for the backrest and the cushion. The dark purple spots mainly represent the sweaty areas.



Blowing mode | Suction mode | Control seat

Figure 74) Thermal camera pictures of the ventilated and the control seat

For the buttocks area is the significantly better solution the suction mode both from the temperature results and from the humidity results. Also, it has to be said, that the blowing mode was set for all time on the maximum intensity. However, the suction mode was reduced. On the other hand, in the thigh area better results provide the blowing mode, the difference is mainly seen in the humidity evaluation. Therefore, considering one blower, it can be definitely suggested the suction mode. However, considering two blowers, it can be recommended to place the suction blower in the buttock area and the small blowing mode blower in the thigh area.

7.2 THERMAL SENSATION AND COMFORT

In all backrest areas, the curves of both modes have mostly the same progress as from thermal sensation as from comfort. The only significant difference is can be seen in the middle back area in thermal comfort, where the suction mode reaches the more comfortable values. Overall, it can be said, that from the point of thermal sensation, between the suction and the blowing mode there is not any significant difference. On the other hand, from the point of thermal comfort, it can be said, that in the beginning, up to six minutes both modes have same values. Nevertheless, after that, the suction mode is slightly comfortable than the blowing mode. Then, in 21 minutes, they change, and the blowing mode steadily rises while the suction mode levels off. From that, it comes out the suggestion more likely for the suction mode. Nonetheless, it can be also recommended the solution, which was mentioned before, that after a while the suction mode turns to the blowing mode. Since the blowing mode seems to be more comfortable for longer use.

The cushion area has mostly the same results as from the temperature and humidity assessment. It means, that from both points of view the better solution is the suction mode. Nevertheless, it has to be said, that in the beginning, both modes are quite similar. The difference stars from 6 minutes, after which is significantly more comfortable the suction mode. Therefore it can be recommended for the cushion part.

7.3 OVERALL

All things considered, it can be concluded that for the backrest in the case of one standard blower, it can be recommended the suction mode. In the beginning, it should be set on the maximum intensity and after 14 minutes the intensity should be slightly reduced. However, if it is possible the option with two blowers, one should be placed in the middle back area for suction and one in the lower back area for blowing. Additionally, the option of the combined blower, when in the beginning it is used in the suction mode and then for longer use in blowing mode.

For the cushion, in the case of the standard blower, it can be definitely recommended the suction mode for all the time. In the beginning, it should be set for the highest intensity and then after 15 minutes reduced at the lower intensity. Considering two blowers, one should be placed in buttocks area for suction and the second in the thigh area for blowing.

These recommendations are supported also by the evaluation of the wanted action. In the backrest area are both cases mostly the same. Nevertheless, in the beginning, the suction mode desires less change of the thermal state. It means that suction mode provides more optimal conditions. On the other hand, in the cushion area, it can be seen, that the change is less desired significantly in the suction mode, which corresponds with previous evaluations.

Also, it has to be mentioned, that in the heat flux measurement there are no significant differences. It could be used rather in the evaluation of the air distribution homogeneity.

Overall, it can be said, that the suction mode has the stronger effect on the cooling feeling. From that reason, it is better especially in the beginning, after that, when the ambient conditions are not in such high temperatures, his intensity should be reduced to provide comfortable state even by higher temperatures than in the blowing mode. It follows that the blowing mode is useful mainly for the long drives because it does not have such a strong cooling feeling.

CONCLUSION

In these days, thermal comfort of the driver and passengers plays the important role during the car development. However, designed thermal-comfort units have to be simultaneously substantially efficient, then it was before, because of energy saving. Which means, that the vehicle produces fewer exhaust emissions in combustion engines, or extend the range in electric cars. To secure this energy saving, thermal-comfort units have to operate comprehensively with particular focus to local thermal comfort. Therefore, the objective of this work was to measure and evaluate the thermal comfort of people exposed to the ventilated seat and to compare two modes of blowing and suction with the special focus on local thermal comfort.

To understand overall thermal comfort issue in automobiles, it was started from the beginning with the human body thermal interaction. It was described and summarised heat transfer with surroundings, heat transfer within the human body and thermoregulation with the special look at different ambient conditions. It was also pointed on examples that human body reacts differently to the hot and cold stimuli as well as to its individual parts.

Then, it was introduced the field of thermal comfort, where it was discussed main approaches and methods used in the thermal comfort assessment. Nonetheless, as the thermal comfort is the subjective quantity, there is still no international standard which allows to assess thermal comfort specifically for the vehicle cabin environment easily. Therefore, the measurement methodology was based on the long-term experience of the climate chamber and thermal comfort laboratories at BUT FME as well as it was adapted to their possibilities.

After that, for the better overall understanding of thermal comfort inside the vehicle, it was stepped to the comprehensive evaluation of thermal-comfort units, which can be found in these days within an automobile. Besides, it can be also considered as a part of active safety, when it prevents the driver from fatigue and loss of attention. Finally, it was reached the overall evaluation that it is crucial to focus on the local thermal-comfort units, such as heated and ventilated seats, heated steering wheel and neck-level heating, which quickly and directly affect the driver and passengers comfort. Together with the HVAC unit, which provide comforted ambient conditions, they are the way how to secure, as it was said, well thermal comfort conditions, while reducing the energy compulsion, which is in these days a pivotal issue, especially for hybrid and electric cars.

Afterwards, it was described the measurement methodology, which was used in this work. The measurement procedure consisted of three main parts should simulate the real situation when a person goes to the car from home or office during a hot summer day, get in, turn on the air conditioning to cool down the interior of the vehicle, and drive for 30 minutes. The measurement was set in the climate chamber, which allowed to simulate mentioned hot summer conditions as well as to simulate the air conditioning turned on. For the evaluation of temperature and humidity were used sensors while for the thermal comfort was used the questionnaire survey. In total, the measurement participated nine persons.

The experimental measurement was evaluated in two separate parts. Firstly from the point of temperature and humidity and secondly from the thermal sensation and comfort point of view. There were shown all results, which were depicted in individual figures. They were divided into individual areas of the backrest and the cushion as well as into the backrest and the cushion areas as wholes. After each part, it was done the overall evaluation of all depicted results.

The final results assessment was done in the individual chapter separately for temperature and humidity, and thermal sensation and comfort. Then it was done resulting overall appraisal considering all ascertained outcomes. Anyway, the general recommendation is followed:

For the backrest in the case of one standard blower, it can be recommended the suction mode. However, if it is possible the option with two blowers, one should be placed in the middle back area for suction and one in the lower back area for blowing. Additionally, the option of the combined blower, when in the beginning it is used in the suction mode and then for longer use in blowing mode.

For the cushion, in the case of the standard blower, it can be definitely recommended the suction mode for all the time. Considering two blowers, one should be placed in buttocks area for suction and the second in the thigh area for blowing.

The suggestion for the further development is to continue with the measurement as it was used. However, for the next time, it will be useful to change the ambient conditions from high temperatures simulating hot summer to just warm enough temperatures to simulate, for example, a day during spring with ambient temperatures around 25 °C. Therefore, the tested persons will be able to fully concentrated to the different feeling between the suction and blowing mode. That will enable to observe thermal comfort from another situation and provide another data to find more significant differences between these two modes. This measurement could also be extended about observation of the air distribution homogeneity, which is another parameter influencing the final thermal comfort.

REFERENCES

[1] CROITORU, Cristiana, Ilinca NASTASE, Florin BODE, Amina MESLEM a Angel DOGEANU. Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives. *Renewable and Sustainable Energy Reviews* [online]. 2015, [2018-04-10]. DOI: 10.1016/j.rser.2014.10.105. ISSN 13640321 Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032114009332

[2] ALAHMER, Ali, Mahmoud ABDELHAMID a Mohammed OMAR. Design for thermal sensation and comfort states in vehicles cabins. *Applied Thermal Engineering* [online]. 2012, [2018-05-16]. DOI: 10.1016/j.applthermaleng.2011.11.056. ISSN 13594311. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1359431111006843

[3] POKORNÝ, Jan. *Coupling of the Models of Human Physiology and Thermal Comfort*. Brno, 2012. Doctoral dissertation. Brno University of Technology, Faculty of mechanical Engineering. Dissertation supervisor prof. Ing. Miroslav Jícha CSc.

[4] Auto.cz [picture]. *Nové Audi A7 Sportback odhalilo český ceník. Jak si stojí proti konkurenci?* [online]. [2018-05-03]. Available from: http://www.auto.cz/nove-audi-a7-sportback-cesky-cenik-jak-stoji-proti-konkurenci-120320/foto?foto=37

[5] Universal ray [picture]. *The electromagnetic spectrum* [online]. [2018-04-07]. Available from: http://www.universalray.com/theory.html

[6] PAVELEK, M. a kol. *Termomechanika*. Skripta, FSI, VUT Brno, 2003.

[7] Termoregulace. *Wikiskripta* [online]. [2018-02-27]. Available from: https://www.wikiskripta.eu/w/Termoregulace

[8] HRUBANOVÁ, K. *Databáze tepelných parametrů oblečení pro systém iHVAC*. Brno: Brno University of Technology, Faculty of mechanical Engineering, 2017. 77 p. Thesis supervisor Ing. Jan Fišer, Ph.D.

[9] Convective Heat Transfer. *Engineers Edge* [online]. [2018-03-09]. Available from: https://www.engineersedge.com/heat_transfer/convection.htm

[10] BERNACIKOVÁ, Martina. *Fyziologie a patofyziologie člověka v extrémních podmínkách*. Slide Player [online]. 2010 [cit. 2018-02-20]. Available from: http://slideplayer.cz/slide/5652843/

[11] KUBÁŠEK, Pavel. *Transport látky*. Základy fyzikální chemie [online]. [2018-03-09]. Available from: https://is.muni.cz/do/rect/el/estud/prif/js11/fyz_chem/web/dynamika/transport.htm

[12] JANOTKOVÁ, Eva. *Technika prostředí: 1. část* [online]. 2011 [2018-03-10]. Available from: http://studyenergyweb.fme.vutbr.cz/file/110/

[14] GERRETT, Nicola, Yacine OUZZAHRA, Bernard REDORTIER, Thomas VOELCKER a George HAVENITH. Female thermal sensitivity to hot and cold during rest and exercise. *Physiology & Behavior* [online]. 2015, [2018-04-12]. DOI: 10.1016/j.physbeh.2015.08.032. ISSN 00319384. Available from: http://linkinghub.elsevier.com/retrieve/pii/S003193841530086X

[15] KENNEY, Larry. Chapter 42 – Heat and Cold. *Encyclopaedia of Occupational Health and Safety* [online]. [2018-03-12]. Available from: http://www.ilocis.org/documents/chpt42e.htm

[16] FOJTLÍN, M. *Stanovení součinitelů přenosu tepla radiací a konvekcí z povrchu tepelného manekýna*. Brno: Brno University of Technology, Faculty of mechanical Engineering, 2014. 63 p. Thesis supervisor Ing. Jan Fišer, Ph.D.

[17] TANNAM, Michelle. *Human Thermoregulatory Response to Infrared Radiant Heating*. Dublin, 2012. Trinity College Dublin, Department of Mechanical and Manufacturing Engineering.

[18] HÅKAN O. NILSSON. *Comfort climate evaluation with thermal manikin methods and computer simulation models*. Stockholm: Arbetslivsinstitutet, förlagstjänst, 2004. ISBN 9170457034.

[19] FIALA, Dušan. *Dynamic Simulation of Human Heat Transfer and Thermal Comfort*. Leicester, 1998. Doctoral dissertation. De Montfort University, Institute of Energy and Sustainable Development.

[20] Research Gate [picture]. *Practical evaluation of the thermal comfort parameters* [online]. [2018-04-12]. Available from: https://www.researchgate.net/figure/Predicted-percentage-dissatisfied-PPD-as-a-function-of-predicted-mean-vote-PMV_fig1_305755583

[21] DANCA, Paul, Andreea VARTIRES a Angel DOGEANU. An Overview of Current Methods for Thermal Comfort Assessment in Vehicle Cabin. *Energy Procedia* [online].

2016, [2018-04-20]. DOI: 10.1016/j.egypro.2015.12.322. ISSN 18766102. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1876610215029872

[22] FOJTLÍN, Miloš, Jan POKORNÝ, Jan FIŠER, Róbert TOMA, Ján TUHOVČÁK a P. DANČOVÁ. Impact of measurable physical phenomena on contact thermal comfort. *EPJ Web of Conferences* [online]. 2017, [2018-04-03]. DOI: 10.1051/epjconf/201714302026. ISSN 2100-014X. Available from: http://www.epj-conferences.org/10.1051/epjconf/201714302026

[23] Auto.cz [picture]. *Nové Audi A7 Sportback odhalilo český ceník. Jak si stojí proti konkurenci?* [online]. [2018-04-05]. Available from: http://www.auto.cz/nove-audi-a7-sportback-cesky-cenik-jak-stoji-proti-konkurenci-120320/foto?foto=33

[24] Texas Instruments. *Understanding flap actuators and what drives them in automotive HVAC systems* [online]. [2018-04-01]. Available from: https://e2e.ti.com/blogs_/b/behind_the_wheel/archive/2017/04/13/understanding-flap-actuators-and-what-drives-them-in-automotive-hvac-systems

[25] Stack Exchange [picture]. *How can I determine my HVAC layout?* [online]. [2018-03-31]. Available from: https://mechanics.stackexchange.com/questions/24015/how-can-i-determine-my-hvac-layout

[26] RepairPal. *Heater Core Replacement Cost* [online]. [2018-03-31]. Available from: https://repairpal.com/estimator/heater-core-replacement-cost

[27] Quora. *Heater How does an air cooled car motor, produce heat to the passenger compartment?* [online]. [2018-04-01]. Available from: https://www.quora.com/How-does-an-air-cooled-car-motor-produce-heat-to-the-passenger-compartment

[28] SAJDL, Jan. Autolexicon. *Klimatizace A/C (AC AirCondition)* [online]. [2018-03-30]. ISSN 1804-2554 Available from: http://www.autolexicon.net/cs/articles/klimatizace-ac-ac-aircondition/

[29] Why High End?. *Dual Zone Climate Control* [online]. 2010 [2018-03-30]. Available from: http://www.whyhighend.com/dual-zone-climate-control.html

[30] Caricos [picture]. *2015 Volkswagen Passat* [online]. [2018-03-30]. Available from: http://www.caricos.com/cars/v/vw/2015_volkswagen_passat/images/91.html

[31] Eberspacher. *Airtronic* [online]. [2018-03-21]. Available from: https://www.eberspacher.com/fileadmin/data/countrysites/EB_UK/pdf_files/info_pdf_ebuk/heating_pdf_ebuk/motorhome_heating_uk_22374.pdf

[32] Eberspächer. *Airtronic technical data* [online]. [2018-03-21]. Available from: https://www.eberspacher.com/fileadmin/data/countrysites/EB_UK/pdf_files/info_pdf_ebuk/heating_pdf_ebuk/heater_range_commercial_uk_22387.pdf

[33] Hammond Auto [picture]. *Webasto Heating Systems* [online]. [2018-03-20]. Available from: https://www.hammondauto.net/services/webasto-dealler

[34] Matsch und Piste [picture]. *Airtronic* [online]. [2018-03-20]. Available from: https://matsch-und-piste.de/wp-content/uploads/2016/02/Schnitt_Airtronic.jpg

[35] Webasto. *Car parking heater* [online]. [2018-03-20]. Available from: https://www.webasto-comfort.com/fileadmin/webasto__media/INT_Global/Documents/car-parking-heater-brochure.pdf

[36] Webasto. *Fuel Operated Heating* [online]. [2018-03-20]. Available from: https://www.webasto-comfort.com/int/heating/car-parking-heater/fuel-operated-heating/

[37] Matsch und Piste [picture]. *Thermo Top Evo* [online]. [2018-03-20]. Available from: https://matsch-und-piste.de/wp-content/uploads/2016/02/Schnitt_ThermoTopEvo.jpg

[38] Webasto. *eThermo Top Eco* [online]. [2018-03-20]. Available from: https://www.webasto-comfort.com/int/product-overview/product/show/ethermo-top-eco/?tx_webastoproducts_webastoproduct%5Bcontroller%5D=Product&cHash=5716dce38c830b0b48af4fc54c882793

[39] Koberger [picture]. *Webasto* e*Thermo Top Eco* [online]. [2018-03-20]. Available from: https://www.koberger-hamburg.de/webasto-ethermo-top-eco-30-p.html

[40] MILLER, Richard. Google Patents. *Heated steering wheel for vehicles* [online]. 1962 [2018-03-28]. Available from: https://patents.google.com/patent/US3165620

[41] Audi world [picture]. *Heated steering wheel* [online]. [2018-03-25]. Available from: https://www.audiworld.com/forums/a4-b9-platform-discussion-212/heated-steering-wheel-inconsistent-heat-distribution-2910910/page2/

[42] Buy Korea [picture]. *Heated steering wheel* [online]. [2018-03-28]. Available from: http://www.buykorea.org/product-details/heating-wire-harness-heated-steering-wheel-car-seat-heating-system--3095215.html

[43] Daimler [picture]. *Airscarf* [online]. [2018-03-25]. Available from: http://media.daimler.com/marsMediaSite/de/instance/ko.xhtml?oid=9271840&relId=1001&fromOid=9271840&borders=true&resultInfoTypeId=172&viewType=thumbs&sortDefinition=manualsort-1&thumbScaleIndex=0&rowCountsIndex=5

[44] Eberspächer. *Decentral systems – Heating modules for seat heating* [online]. [2018-03-25]. Available from: https://www.eberspaecher.com/en/products/electrical-heaters/decentral-heating-systems.html

[45] Mercedes 500SEC. *Airscarf* [online]. [2018-03-25]. Available from: http://500sec.com/airscarf/

[46] Car and driver [picture]. *Airscarf* [online]. [2018-03-25]. Available from: http://media.caranddriver.com/images/media/229279/2009-mercedes-benz-sl63-amg-airscarf-illustration-photo-229286-s-1280x782.jpg

[47] Buy Korea [picture]. S*eat heater* [online]. [2018-04-06]. Available from: http://www.buykorea.org/product-details/seat-heater-wire-harness-felt-heating-system-car-seat-option-seat-heat--3095214.html

[48] PETERS, A. *Untersuchungen an Demonstratorsitzen zu neuartigen Belüftungs-/ Heiz- und Komfort-Sensorik-Konzepten*. Braunschweig: Technische Universität Braunschweig, 2017. 118 p. Thesis supervisor prof. Meinhard Schilling.

[49] Manager magazin [picture]. *Massagen mit Druckluft und heißen Steinen* [online]. [2018-04-03]. Available from: http://www.manager-magazin.de/fotostrecke/autositze-die-wellness-moebel-von-morgen-fotostrecke-134410-2.html

[50] Electric vehicle news. *How to power heating and A/C in an electric car* [online]. [2018-04-06]. Available from: http://www.electric-vehiclenews.com/2009/06/how-to-power-heating-and-ac-in-electric.html

[51] Wikipedia. *Veličina* [online]. [2018-05-12]. Available from: https://cs.wikipedia.org/wiki/Veli%C4%8Dina

[52] Mathisfun. *Standard deviation and variance* [online]. [2018-05-15]. Available from: https://www.mathsisfun.com/data/standard-deviation.html

[53] TZBinfo. *Teorie vlhkého vzduchu* [online]. [2018-05-15]. Available from: https://vetrani.tzb-info.cz/teorie-a-vypocty-vetrani-klimatizace/3323-teorie-vlhkeho-vzduchu-i

[54] ŠTĚTINA, Josef. Klimatická komora. *Energetické fórum* [online]. [2018-04-27]. Available from: http://www.energetickeforum.cz/fsi-vut-v-brne/laboratore/klimaticka-komora

[55] Testo. *Testo 435* [online]. [2018-04-30]. Available from: https://www.testo.com/en-UK/testo-435-4/p/0563-4354

[56] Testo. *Compact professional humidity module* [online]. [2018-05-10]. Available from: https://www.testo.com/en-UK/humidity-probe-head/p/0636-9736

[57] Sensirion. *Digital Humidity Sensor SHT7x (RH/T)* [online]. [2018-05-10]. Available from: https://www.sensirion.com/en/environmental-sensors/humidity-sensors/pintype-digital-humidity-sensors/

[58] Mahöle Messtechnik. *Symbiscan TS2e* [online]. [2018-04-30]. Available from: http://www.mahoele.de/EN/index.htm

LIST OF ABBREVIATIONS AND SYMBOLS

Symbol	Unit	Description
AC		Air conditioning
ASHRAE		The American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD		Computational Fluid Dynamics
d.a.		Dry air
DISC		Thermal discomfort index
DTS		Dynamic Thermal Sensitivity
ECU		Electronic Control Unit
HVAC		Heating, ventilation, and air conditioning
IR		Infrared
ISO		International Organization for Standardization
MTV		Mean Thermal Vote
N	[-]	Number of observations
NIR		Near-infrared
NTC		Negative Temperature Coefficient
NUV		Near-ultraviolet
P	[Pa]	Parcial pressure
p	[Pa]	Atmospheric pressure
PMV		Predicted Mean Vote
PPD		Predicted Percentage of Dissatisfied
q	[g/kg $_{\mathrm{d.a.}}$]	Specific humidity
RH	[%]	Relative humidity
s	[-]	Sample standard deviation
T	[°C]	Temperature
TSENS		Thermal sensitivity index
UV		Ultraviolet
$\overline{x}$	[-]	Mean value
x_i	[-]	Sample values